CONTROLLING COMBUSTION-SOURCE EMISSIONS AT AIR FORCE SITES WITH A NEW FILTER CONCEPT

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The U.S. Air Force employs many combustion sources at its facilities, including boilers, diesel engines, turbines, incinerators, and motor vehicles, that produce exhaust gases containing undesirable components. Components of concern include nitrogen oxides (NOx), carbon monoxide (CO), PM-10 particulate matter, sulfur dioxide (SO_2), and a long list of compounds considered toxic by nature. Recently, Sorbent Technologies Corporation (Sorbtech) developed a new filter technology for the Air Force to control emissions from jet engine test cells. The objective of the project described in this report was to conduct a preliminary evaluation of other possible Air Force applications of the new filter technology. The project was conducted at Sorbtech's laboratories in Ohio and at McClellan AFB in California. Of more than 10 combustion waste-gas streams at McClellan AFB, seven were characterized and three were selected for initial study by Sorbtech. A special filter-test apparatus was designed, constructed, evaluated in the laboratory. It was then installed and employed at McClellan AFB to treat waste-gas slipstreams in the three applications. The applications were: (1) a large, stationary diesel engine; (2) a natural-gas-fired burner-heater; and (3) a mobile diesel generator.

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19. ABSTRACT (cont'd)

The results of the initial studies showed that the use of the new technology to control emissions from stationary diesel engines and from burner-heaters at McClellan AFB is very promising. Good removals of NOx and particulates were seen in many cases. NOx reduction was observed to be a function of the face velocity of the exhaust gas and of the thickness of the filter bed. Additional research will be required to apply the new technology to mobile diesel units owing to the nature of the units and to apparent high moisture levels in their exhaust gases.

PREFACE

This report was prepared by Sorbent Technologies Corporation, Twinsburg, OH 44087, under SBIR Contract Number F08635-93-C-0104 for the Air Force Environmental Compliance R&D Branch (AL/EQS), 139 Barnes Drive, Tyndall AFB, FL 32403-5319.

This Phase I final report describes the experimental approach and results of an initial study examining the possible application of a new filter concept to several different Air Force combustion sources for the control of NOx and other pollutant emissions. The work was performed between May, 1993 and November, 1993. The Air Force Technical Project Officer was Dr. Joseph D. Wander.

Principal research staff members at Sorbent Technologies Corporation who participated in the project were Sidney G. Nelson, David A. Van Stone, Brian W. Nelson and Kenneth A. Peterson. Guidance and assistance in conducting the project was provided by the Air Force Technical Project Officer; by Terry Emmitt, John Carroz and Alan Leung of McClellan AFB; and by Alan Canfield of Tyndall AFB.

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EXECUTIVE SUMMARY

A. OBJECTIVE

The objective of this effort was to determine the suitability of reactive sorbent beds containing vermiculite, MgO-coated vermiculite (MagSorbent), and activated carbon, alone or in sequence, for the removal of combustion-derived oxides of nitrogen (NOx) exhausting from representative Air Force stationary sources.

B. BACKGROUND

Evolving federal standards for tropospheric ozone concentrations and some more-stringent local standards for oxides of nitrogen (NOx) are creating regulatory pressure to decrease rates of emission of NOx from stationary and mobile combustion processes. Limitations in cost and adaptability of conventional catalytic NOx-control methods led to development of reactive sorbent materials as a largely condition-independent technology now being evaluated as a means to control emissions from jet engine test cells (JETCs). A JETC is probably the worst possible application because the volumes involved are very large; flow rate, temperature, and composition change drastically over short periods of operation; and the engine is sensitive to changes of temperature or pressure. However, the measure of success observed in the JETC program suggested applicability to both stationary and mobile near-steady-state combustion exhausts, which are far less demanding of the NOx-control system. This report details a small-scale exploratory investigation of carbon and mineral-based sorbent technology as a means to remove NOx from gas streams exiting a representative group of near-steady-state, stationary processes.

C. SCOPE

This report surveys 11 operational sources at McClellan AFB CA and selects for initial testing three that offer the largest payoff in decrease of net emission of NOx. A subscale treatment system was designed, assembled, and applied to slipstreams from the exhaust stacks of a boiler and a diesel electric power generator. Removal of NOx, carbon monoxide (CO), and (qualitatively) soot and pressure drop across the bed were noted for each of the three sorbents (and several combinations) as a function of bed thickness and flow rate.

D. METHODOLOGY

Tests were conducted on actual exhaust gases split from operational exhaust stacks on a boiler and a diesel electric generator. A specially constructed test system was used for all tests, allowing bed thicknesses of 3, 6, 9, or 12 inches. Individual gases were measured with an Enerac 2000A Chemical Cell Analyzer. Pressure drops were measured directly by difference.

E. TEST DESCRIPTION

Beds were inserted into the test apparatus and filled with the sorbent(s) selected for each test. Gas was removed from the main stack by a constant-rate blower that delivered a minimal velocity to the test apparatus. The analyzer was calibrated at the beginning and end of each run, and occasional samples were drawn into Draeger tubes to provide an independent check of results. Material for analysis was drawn at sampling points at either external face of the sorbent beds. Pressure drop was measured concurrently as the difference between two sampling points, one at either face of the bed. Pollutant removal was determined indirectly, by comparing influent and effluent concentrations.

F. RESULTS

As in previous studies, vermiculite was an effective filter for soot, but only marginally effective in removing NOx and ineffective against CO. MagSorbent was marginally effective as a soot filter, but reasonably effective as a NOx removal device at face velocities of 2 fps or less. Carbon proved to be the best NOx removal material. Pressure drops were generally about an inch (WG) per fps of air flow for a 6-inch bed of any sorbent.

G. CONCLUSIONS

Results in hand suggest that these sorbents in some combination could form the basis for a practical device to remove NOx from a range of combustion streams. However, the status of carbon so used remains to be determined, whereas earlier results suggest that used MagSorbent will be nonhazardous and beneficial in horticultural applications. The operating characteristics (except possible water-sensitivity) appear to be compatible with the applications evaluated.

H. RECOMMENDATIONS

Technical risks appear to be minimal, and the concept appears to be compatible with at least some of the applications originally considered. This program will be recommended for continued development by the Air Force.

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SECTION I

INTRODUCTION

A. PROJECT OBJECTIVES

The overall SBIR Project objective (Phases I and II) is to determine if the new filter developed for jet-engine test cells can also be used effectively in other Air Force pollution-control applications. Applications of particular interest include the exhaust gases of natural-gas-fired boilers and heaters, diesel engines, mobile vehicles, and incinerators.

The principal technical objectives of the Phase I research were to collect background information and data important for the design of a prototype filter system and to obtain preliminary removal data via small slipstream trials. More specifically, the Phase I technical objectives were (1) to characterize the exhaust-gas streams from several different combustion units at McClellan AFB; (2) to design, construct, pretest, and install a small test filter on small slipstreams of exhaust gas from two or more of the units; and (3) to conduct a test program examining the effects of changes in filter bed composition, in filter bed thickness, and in exhaust gas temperature on filter performance.

B. BACKGROUND

The U.S. Air Force employs many combustion sources at its facilities. Examples are boilers, diesel engines, turbines, incinerators, and motor vehicles. Most of these sources produce exhaust gases containing undesirable components. Components of concern in recent years include nitrogen oxides (NOx), carbon monoxide (CO), FM-10 particulate matter, sulfur dioxide (SO_2) and a long list of compounds considered toxic by nature.

Environmental regulations and emission limits often make it difficult for the Air Force to add needed new facilities that generate emissions. Sometimes the only way new facilities can be added is if undesirable emissions of older facilities are reduced or if special credits are purchased, if they are available to be purchased. Reducing the levels of NOx, CO and other pollutants at specific Air Force sites can provide valuable credits for the sites. This is particularly important for locations such as McClellan AFB in California, which is in an ozone nonattainment area.

It is unfortunate today that, in many cases, simple, low-cost methods are not available to adequately control many of the pollutants of concern. For example, the best commercially available technology to reduce NOx emissions in exhaust gases is selective catalytic reduction (SCR). However, SCR is very expensive, is limited to certain temperature ranges, is only partially effective in reducing NOx, and requires ammonia additions to the exhaust gas that often slip into the atmosphere. A definite need exists today for simpler, less costly technologies to control NOx and other contaminants in exhaust gases.

The Air Force has long been aware of possible environmental costs of the emissions that are produced during the testing of aircraft engines in test cells. As a result, it has supported efforts in the past to develop suitable, low-cost approaches to control aircraft emissions, particularly NOx, CO and fine particulates.

One promising new technology for controlling test-cell emissions was developed by Sorbent Technologies Corporation (Sorbtech). The new technology is a simple filter design consisting of thin panel beds of vermiculite, vermiculite–MgO and/or activated carbon. The bed materials capture contaminants or convert them into innocuous molecules as exhaust gases pass through the beds at the end of an exhaust-gas chimney. In tests at Tyndall AFB, the filters were found to remove 40 to 83 percent of the NOx, more than 50 percent of the particulates, and significant amounts of CO that were present in jet-engine exhaust gases.*

The promising results with the new test-cell filter prompted interest in exploring other Air Force applications for the new technology. This report describes an investigation that was carried out, as a Phase I Small Business Innovation Research (SBIR) Project, to examine several potential applications at McClellan AFB.

C. SCOPE

This report describes results from a Phase I SBIR effort. A series of 11 sources was visited, from which seven were selected for slipstream testing. Of these, one was off line at the time of testing. Efficiency of NOx removal (measured as (1-[NOx] leaving the filters/[NOx] entering the filters) was determined for filters using several combinations of vermiculite, vermiculite–MgO, and activated carbon.

*Nelson, B.W., Van Stone, David and Nelson, S.G., Development and Demonstration of a New Filter System to Control Emissions During Jet Engine Testing, CEL-TR-92-49, Air Force Engineering & Service Center, Tyndall AFB, FL, Final Report, October, 1992.

SECTION II

CHARACTERIZATIONS OF SELECTED McCLELLAN AFB EXHAUST GASES

A. COMBUSTION SOURCES AT McCLELLAN AFB

Eleven combustion sources producing exhaust gases of concern at McClellan AFB were identified. These were

1. Large, Mobile Diesel-Fuel-Fired Electrical Generators. McClellan AFB has about a dozen of these units. Stored outside, these units are on wheels and can be moved quickly to most base locations where relatively small amounts of auxiliary power are needed. A line of mobile generators is shown in Figure 1.

2. Large, Stationary Diesel-Fuel-Fired Engines. Three large units are housed in a single, well-maintained building (Building 262). These units do not see continuous duty, but are employed extensively. Figure 2 shows these units.

3. Small Natural-Gas-Fired Boilers. Two small boilers in Building 263B provide air-conditioning for computer rooms. These boilers are very old and appear to have been originally designed for stoker coal or fuel oil and converted later to natural gas. Only one unit appears operational; the second unit is a spare.

4. Medium Natural-Gas-Fired Boilers. Two relatively new boilers in Building 1403 supply steam for various base operations. The two boilers are similar in design and size.

5. Diesel-Fuel-Fired Mobile Cranes. McClellan AFB has several mobile cranes. The cranes, which are stored outside, are relatively new and are used frequently. A typical mobile crane is shown in Figure 3.

6. Diesel-Fuel-Fired Tow Tractors. McClellan AFB has several of these units. Like the cranes, these units are stored outside and are used extensively, particularly along the flight line. The tow tractors are of different ages, with the oldest ones having dual exhausts and obviously high particulate emissions.

7. Natural-Gas-Fired Burner-Heaters. More than 40 of these units are located in one very large building to assist in drying freshly repainted aircraft. The units are located as clusters high near the building ceiling. Each heater is approximately 10 feet long and 3 feet wide. Sketches of a burner-heater appear in Figure 4. Because the burner-heaters are out of compliance with respect to NOx, they cannot be operated at the present time.

8. Large Natural-Gas-Fired Boilers. McClellan AFB has three large boilers, at least one of which is used almost continuously. Receiving much attention in the past, these boilers have been modified or are currently being modified with flue-gas recycling and reburning systems to reduce NOx levels.

9. Jet-Engine-Test-Cells. Several jet-engine-test-cell (JETC) complexes exist at McClellan AFB. Two complexes are very old and have been or are being phased out. JETC applications of the new technology are being addressed in a separate Air Force program.

Figure 1. Mobile Electrical Generators

Figure 2. Stationary Diesel Engines

Figure 3. A Diesel-Fueled Mobile Crane

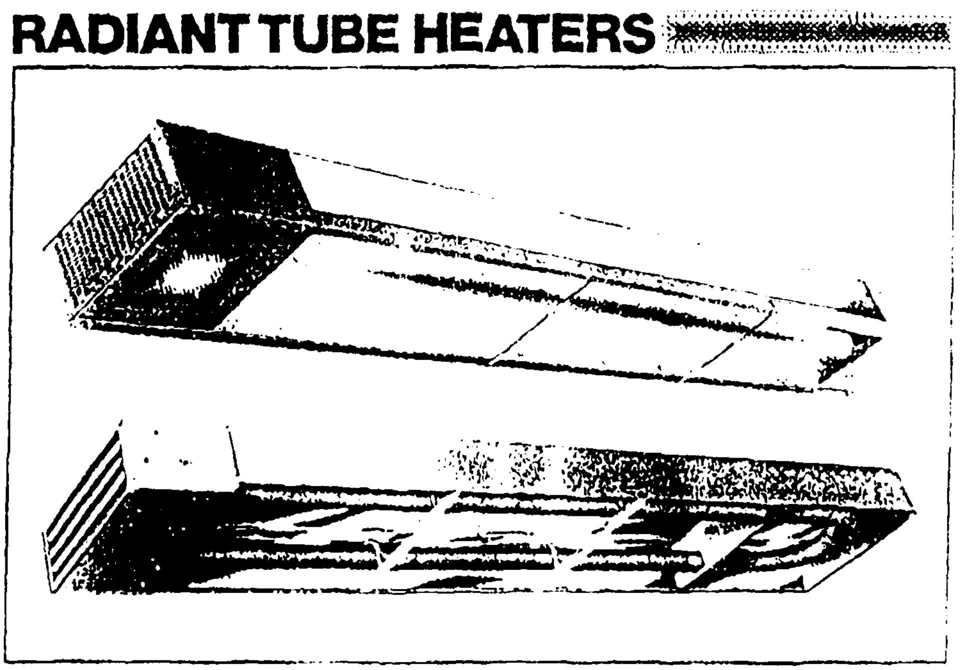

Figure 4. Sketches of Radiant Tube Heaters

10. Incinerator. An incinerator is being used at McClellan AFB in combination with catalytic oxidizers to destroy organic components in effluents derived in cleaning contaminated soils. The facilities are not operated continuously and were not used extensively in 1993.

11. Gasoline-Fueled Automotive Vehicles. McClellan AFB covers many acres, and conventional automobiles and trucks are the most common means of moving from site to site. Undoubtedly automobiles and trucks add significantly to McClellan AFB's overall pollution problems.

Of the 11 combustion sources just described, the initial seven were selected for characterization studies. Jet-engine test cells were not included because they are being considered elsewhere. The incinerator was not included because it was not in operation at the time of this study. The large natural-gas-fired boilers were excluded because McClellan personnel indicated that these units were no longer of major concern because recycling and reburning appears to have improved the situation significantly, and conventional automobiles and trucks were excluded because they will be studied separately as part of the proposed Phase II project.

B. EXHAUST GAS CHARACTERIZATIONS

During the week of 19 July 1993, Sorbent engineers characterized the exhaust gases emitted from eight separate units at McClellan AFB. These units included one of the largest and newest mobile diesel-fuel-fired generators; the largest stationary diesel-fuel-fired engine; a small natural-gas-fired boiler; one of the two existing medium-sized, natural-gas-fired boilers; a late-model diesel-fuel-fired mobile crane and an old-model diesel-fuel-fired tow tractor. Several months earlier, Acurex Environmental Corporation characterized one of the natural-gas-fired burner-heaters in the paint-drying building. The exhaust gases from the large stationary diesel-fuel-fired engine were characterized under three different operating conditions: 25 percent load; 50 percent load; and 75 percent load. This engine is rarely operated at loads above 75 percent.

Tables 1 and 2 summarize the information and data collected during the characterizations performed by Sorbtech and by Acurex.

Observations made from the collected data and from examinations of the various facilities include the following:

1. The small- and medium-sized natural-gas-fired boilers were fairly clean with respect to NOx and particulates, particularly in comparison with the diesel-fuel-fired facilities that were examined.

2. The large stationary diesel-fuel-fired engine facility and the large, mobile diesel-fuel-fired electrical generators produced, by far, the largest quantities of NOx and particulates.

3. The mobile crane and tow tractor produced significant NOx, but they present special NOx-control challenges owing to their construction and manners of usage.

4. The natural-gas-fired burner-heaters produce relatively low levels of NOx, and reducing these NOx levels further by applying the new technology to achieve compliance with environmental regulations would appear feasible.

On the basis of the above observations, three facilities were selected for slipstream testing in Phase I of the Project. They were: (1) A large, stationary diesel-fuel-fired engine; (2) A large, mobile diesel-fuel-fired electrical generator; and (3) a natural-gas-fired burner-heater.

TABLE 1. COMPILATION OF DATA FROM EXHAUST-GAS CHARACTERIZATIONS

	1	2	3	4
Application	Large, Mobile Diesel-Fired Electrical Generator	Large Stationary Diesel Engine	Large Stationary Diesel Engine	Large Stationary Diesel Engine
Equipment	John R. Hollingsworth 200 KW with Cummings 885-325HP Engine-Model MEP009B	White-Superior 405X8-440KW	White-Superior 405X8-440KW	White-Superior 405X8-440KW
Location	Building 684	Building 262	Building 262	Building 262
Power Level	45% Load	25% Load	50% Load	75% Load
Channel Size	5-in ID Exhaust	10-in ID Exhaust	10-in ID Exhaust	10-in ID Exhaust
Flue Gas Velocity	20,000 fpm	3,400 fpm	5,500 fpm	7,200 fpm
Gas Temp, Dry Bulb	610°F	287°F	396°F	479°F
<u>Gas Composition</u>				
O_2	14.7%	17.3%	16.3%	16.6%
Combustibles	0.0%	0.0%	0.0%	0.0%
SO_2	0 ppm	0 ppm	0 ppm	0 ppm
CO	120 ppm	141 ppm	47 ppm	29 ppm
NOx	325 ppm	320 ppm	445 ppm	465 ppm
NOx (corrected to 3% O_2)	940 ppm	1590 ppm	1730 ppm	1940 ppm
Smoke	Some	Some initially	Some	Fairly clear
Flue Gas Flow Rate	2730 SCFM	1850 SCFM	3000 SCFM	3930 SCFM
Hourly NOx Output	4.4 lb/hr	3.0 lb/hr	6.7 lb/hr	9.1 lb/hr
Yearly NOx Output*	19.4 TPY	13.0 TPY	29.3 TPY	40.0 TPY

*Assumes continuous operation

TABLE 1. COMPILATION OF DATA FROM EXHAUST-GAS CHARACTERIZATIONS (Concluded)

	5	6	7	8
Application	Small Natural Gas Boiler	Medium Natural Gas Boiler	Diesel-Fired Mobile Crane	Diesel-Fired Tow Tractor
Equipment	National U.S. Steel Boiler 1,080,000 BTU/Hr –Steam Generator	Peerless Gas Boiler 2,100,000 BTU/Hr –Steam Generator	8.2 l GMC Diesel	Oshkosh Model MB2 with Caterpillar 3208 Ergruss/Dual Exhaust
Location	Building 263B	Building 1403	Building 380	Building 380
Power Level	High Load	Varying Load	High Load	High Load
Channel Size	15-in ID Immediate Exit	18-in ID Stack	3-in D Tailpipe	2.5-in D Tailpipe
Flue Gas Velocity	1,200 fpm	240 fpm	5,500 fpm	4,500 fpm
Gas Temp, Dry Bulb	573°F	167°F	273°F	253°F
<u>Gas Composition</u>				
O_2	16.9%	17.2%	19.2%	18.8%
Combustibles	0.0%	0.92%	0.0%	0.04%
SO_2	0 ppm	0 ppm	0 ppm	0 ppm
CO	3 ppm	180 ppm	45 ppm	234 ppm
NOx	18 ppm	17 ppm	136 ppm	87 ppm
NOx (corrected to 3% O_2)	80 ppm	80 ppm	1430 ppm	740 ppm
Smoke	None	None	Some	High Level
Flue Gas Flow Rate	1470 SCFM	424 SCFM	270 SCFM	153 SCFM (one pipe)
Hourly NOx Output	0.13 lb/hr	0.04 lb/hr	0.18 lb/hr	0.07 lb/hr
Yearly NOx Output*	0.58 TPY	0.16 TPY	0.80 TPY	0.29 TPY

*Assumes continuous operation

TABLE 2. DATA COLLECTED BY ACUREX ENVIRONMENTAL CORPORATION

Application	Wash-Rack Natural-Gas-Fired Heaters
Equipment	Space-Ray Radiant Tube Heater - one unit of about 40, each 175,000 BTU/Hr, Model RSTP17C
Location	Building 375
Power Level	Normal Load
Channel Size	18" x 2" Exhaust Hood
Moisture	6.6 vol %
Gas Temp, Dry Bulb	490°F
<u>Gas Composition</u>	
O_2	15.2%
CO_2	3.2%
CO	<1 ppm
NOx	27 ppm
NOx (corrected to 3% O_2)	85 ppm
Flue Gas Flow Rate	93 SCFM
Hourly NOx Output	0.02 lb/hr
Yearly NOx Output	0.08 TPY

SECTION III

DESIGN AND CONSTRUCTION OF A PANEL-BED-FILTER TEST APPARATUS

A panel-bed-filter test apparatus (PBFTA) was designed and constructed to carry out slipstream tests. Criteria employed in designing this apparatus included the following:

1. Goal-Orientation. The unit had to be able to meet the goals of the project and to measure the effects of changes in exhaust gas velocity, bed composition, and bed size on NOx-removal performance.

2. Flexibility. The unit had to be applicable to all the exhaust gas streams of concern at McClellan AFB, regardless of the location and nature of the exhaust-gas streams.

3. Light-Weight, Sturdiness. The unit had to be designed as several, easily-assembled, relatively light-weight parts, to minimize handling problems. The parts, however, had to be sturdy enough to withstand rough handling and multiple uses at different exhaust-gas sites.

A schematic drawing of the PBFTA is shown in Figure 5. The principal components of the PBFTA were a filter apparatus, which was the key part of the system; a fan (to draw exhaust gases from the stack or main gas duct); piping; and measurement equipment. The measurement equipment (not shown in Figure 5) included thermocouples that were placed into sample ports before and after the filters, a Kurz anemometer that was placed into one of the sample ports in the piping, a manometer connected to ports before and after the filter, and a gas-sampling and -analysis system. Gases entering and leaving the filters were analyzed continuously for NO, NO_2, CO, oxygen and SO_2 with an Enerac 2000A chemical-cell analyzer. A second, similar unit was used as a back-up, and Draeger tubes were used on occasion for analyses checks. The gas sampling and analysis system was designed to supply gas streams to the analyzer with a near-zero draft.

The filter apparatus was designed to hold individual filter beds. It was a box-like structure constructed of carbon steel, having a tapered entrance section, an exit section that was open to the atmosphere, and four separate test and sampling ports (see Figure 6). Individual filter beds were held in separate filter-bed holders. The holders, constructed of stainless steel sheet, angles and screen, held either 3-inch or 6-inch thick beds of sorbent. When used singularly or together, they could provide total bed thicknesses of 3, 6, 9 or 12 inches. A total bed thickness of 12 inches was accomplished by placing 3 inches of sorbent in the space between 3-inch and 6-inch beds. Three different sorbent materials, vermiculite, MgO--vermiculite, and activated carbon, were employed in the sorber holders.

Construction drawings of the filter apparatus and of the individual filter-bed holders appear in Appendix A. The units were constructed by L & L Fab Company of Streetsboro, Ohio, based on drawings prepared by Sorbtech engineers.

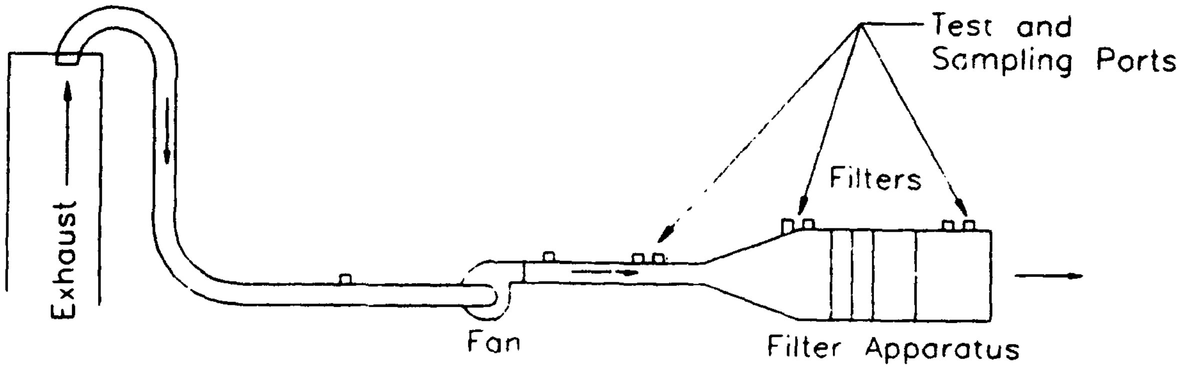

Figure 5. Sketch of the Panel-Bed-Filter Test Apparatus

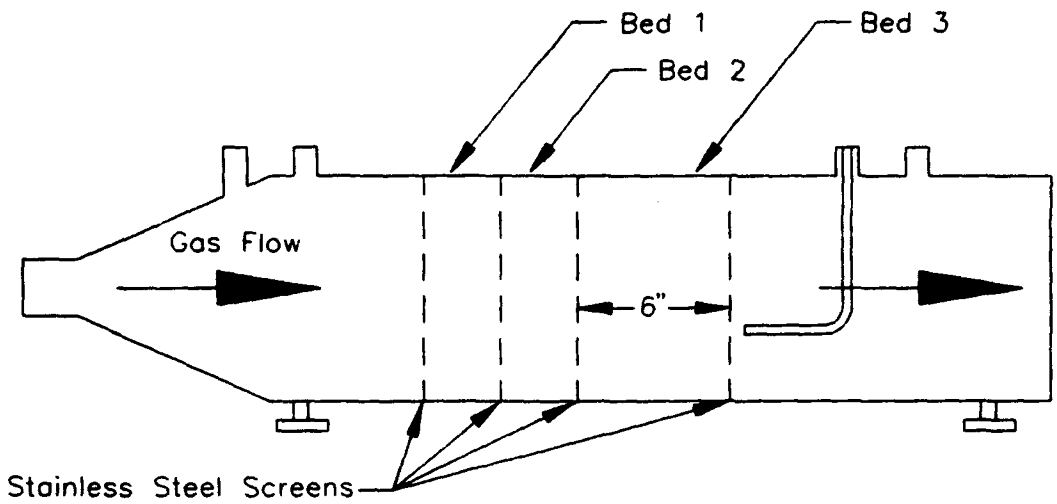

Figure 6. Cross-Section of the Filter Unit

SECTION IV

LABORATORY TESTS

Before the panel-bed-filter test apparatus (PBFTA) was taken into the field for slipstream runs, the apparatus was tested in the laboratory. A total of 60 short-term runs, each 10 to 15 minutes in duration, were performed in two test phases. In Phase 1, 3-inch, 6-inch, 9-inch, and 12-inch beds of vermiculite, MgO–vermiculite, and activated carbon were examined. Mixed beds were employed in Phase 2. All runs were performed at room temperature with atmospheric air, into which controlled quantities of NO were added.

The PBFTA appeared to perform well in laboratory tests. The only problems observed were (1) leakage or slippage of gas between the filter-bed enclosures and the inside surfaces of the filter chamber, particularly when thick sorbent beds and high gas flows were employed; and (2) eddy currents in the exit chamber when very low gas flows were used. The eddy currents occurred when outside air was drawn into the exit chamber by normal conventional currents in the room, particularly when people moved around the unit during a run. The leakage or slippage problems were minimized by placing rubber gasket material between the filter-bed enclosures and the filter-chamber walls. They were also minimized by shaking the beds well before introducing the beds into the chamber. Filter beds tended to expand and then resettle during runs and, in doing so, often resulted in open regions at the top of the beds through which flow was favored. Shaking and tamping down beds beforehand reduced bed expansion and resettling.

A summary of the laboratory test results appears in Appendix B. Graphs showing NOx removal performance as a function of gas velocity are given in Figures 7, 8, 9, and 10.

The test results seen in the laboratory at room temperature were similar to those observed earlier in laboratory and field tests with NOx-containing gases at temperatures below 100°F. They showed that:

1. NOx removal performance decreases with increase in the face velocity of the gas. This is expected because the residence time within a bed of given thickness decreases as the gas velocity increases.

2. NOx removal performance increases with increase of total bed thickness. Again, this is expected because residence time increases with increased bed thickness for a given gas velocity.

3. NOx removal performance was best for activated carbon beds, next best for MgO–vermiculite beds, and poorest for beds of vermiculite alone.

Tests with bed combinations of vermiculite and activated carbon or MgO–vermiculite (MagSorbent) demonstrated relatively promising performance in treating room-temperature gases having NOx levels of 30 to 120 ppm and face velocities within the range 0.5 to 2.0 fps.

With the fan that was used in the PBFTA, high flows of gas through 12-inch beds of materials were difficult to achieve. For this reason, only a limited number of 12-inch-bed runs were performed and all were with activated carbon.

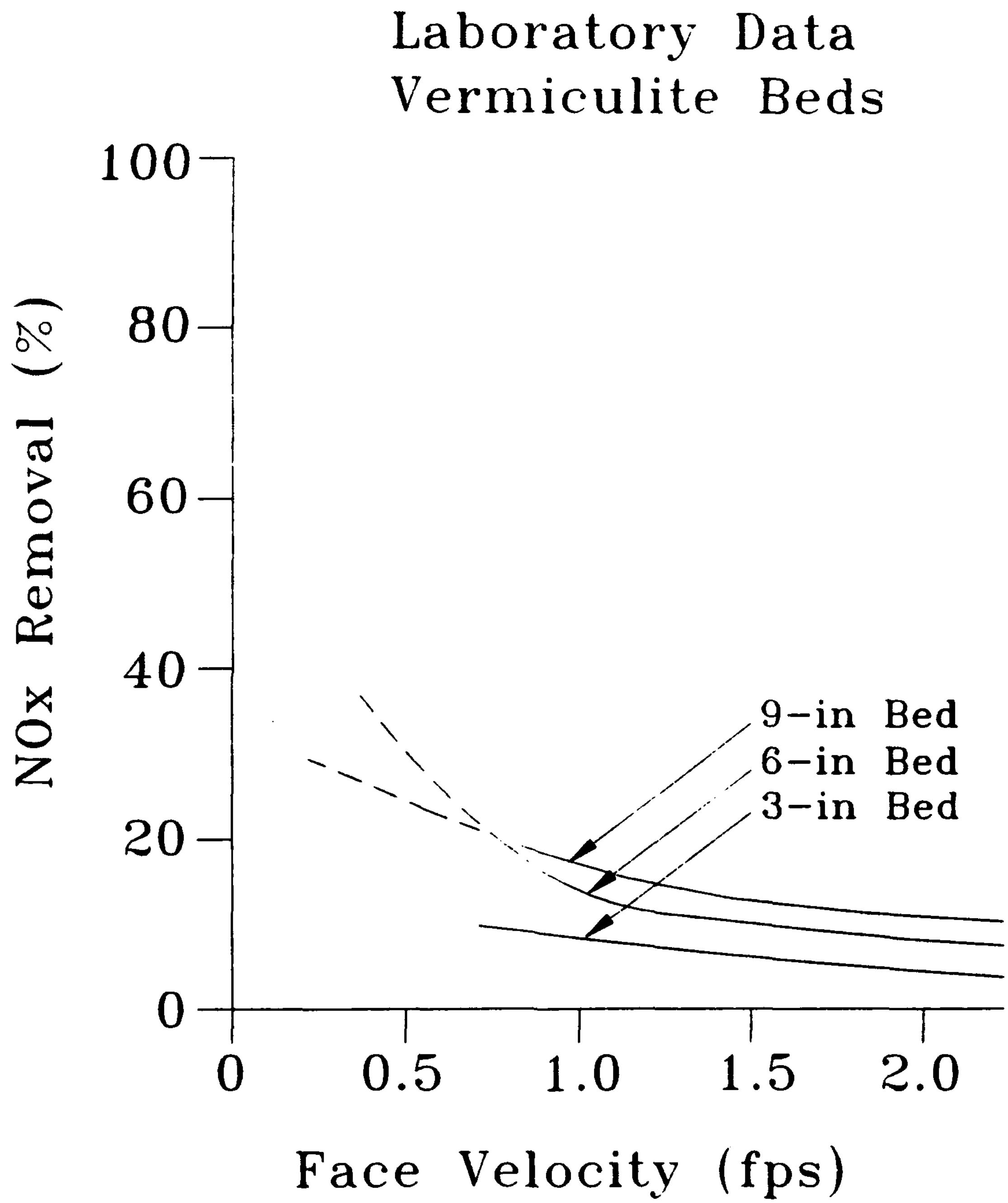

Figure 7. NOx Removal as a Function of Exhaust-Gas Velocity for Vermiculite Beds – Laboratory Data

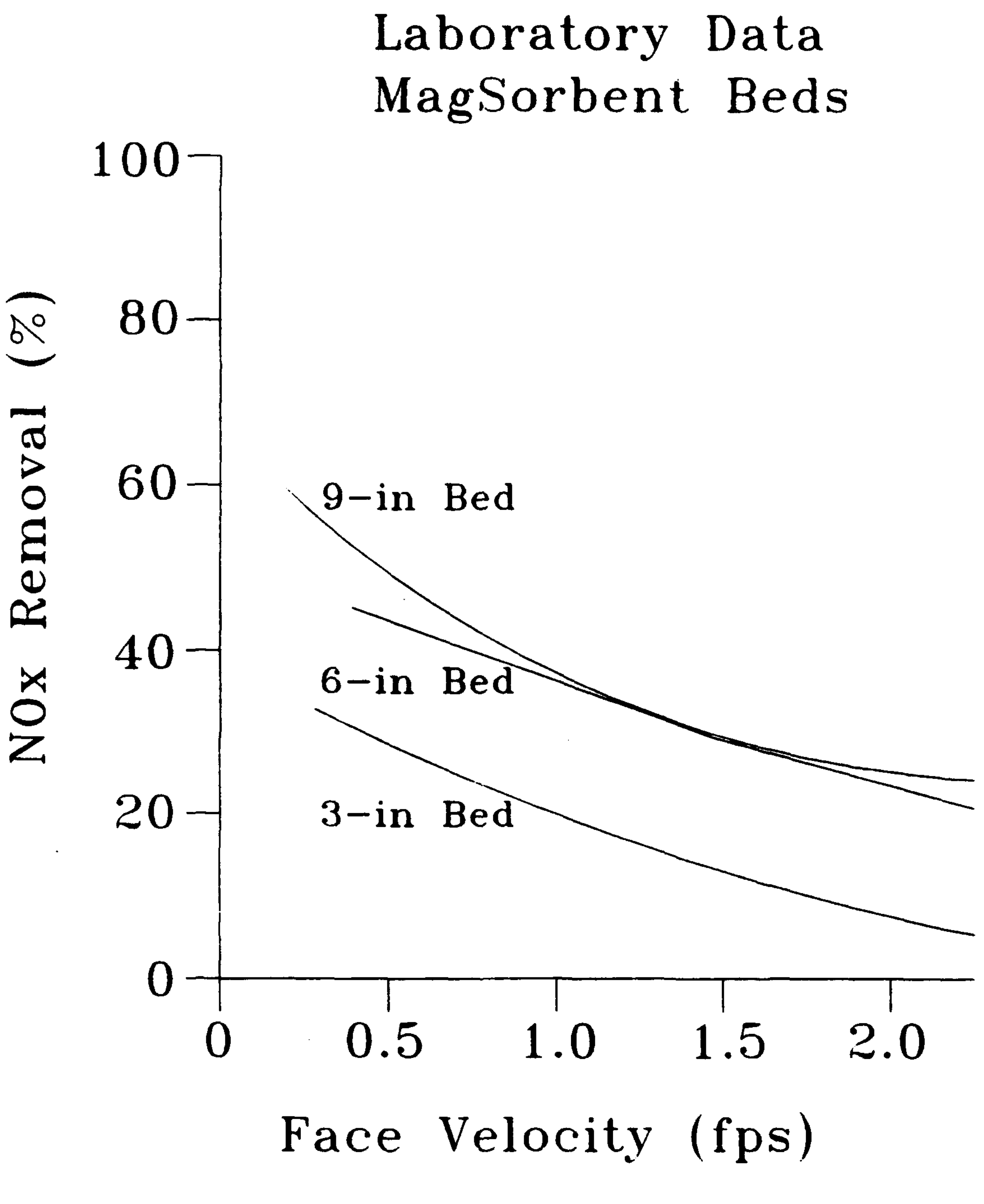

Figure 8. NOx Removal as a Function of Exhaust-Gas Velocity for MgO–Vermiculite (MagSorbent) Beds – Laboratory Data

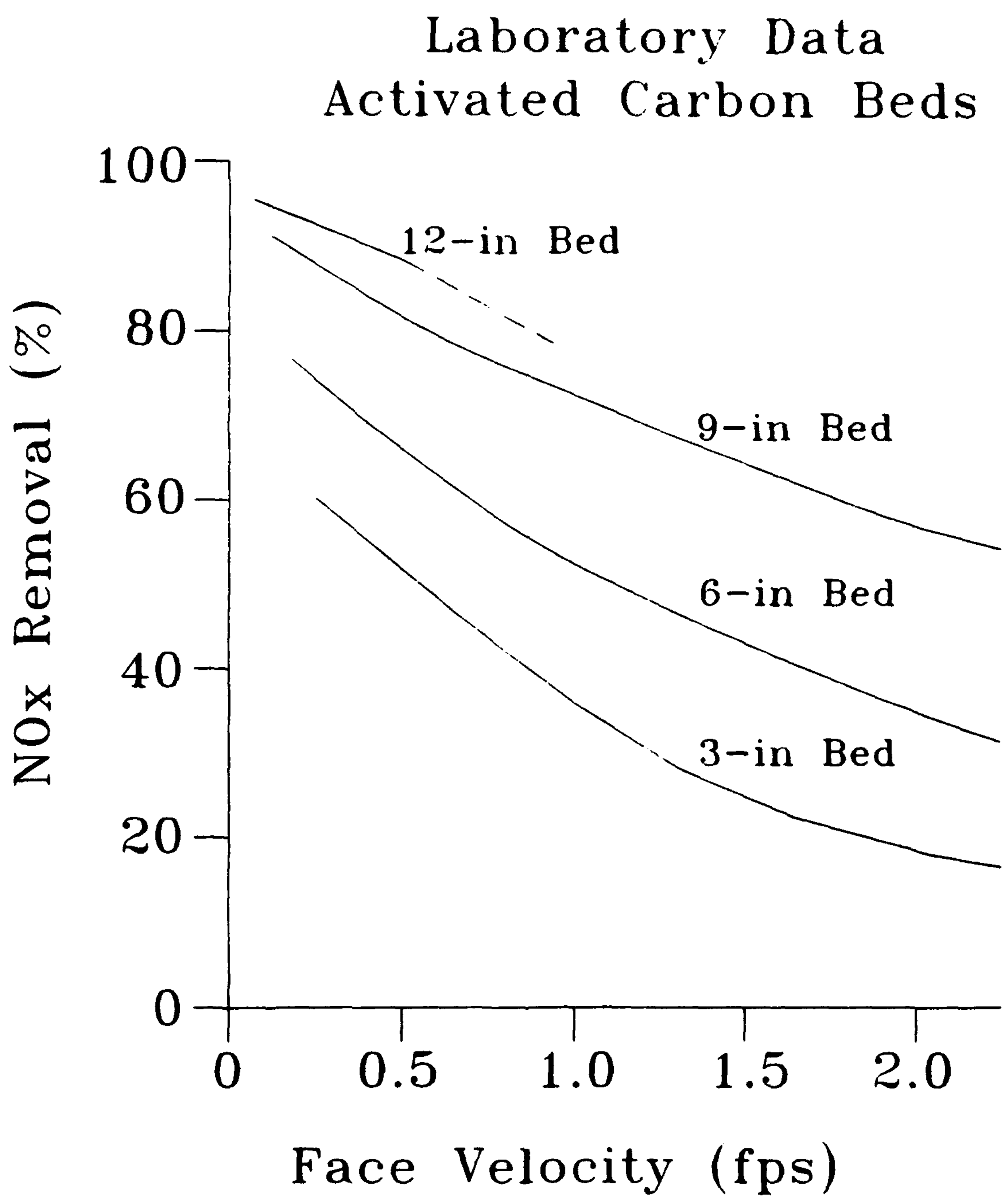

Figure 9. NOx Removal as a Function of Exhaust-Gas Velocity for Activated Carbon Beds -- Laboratory Data

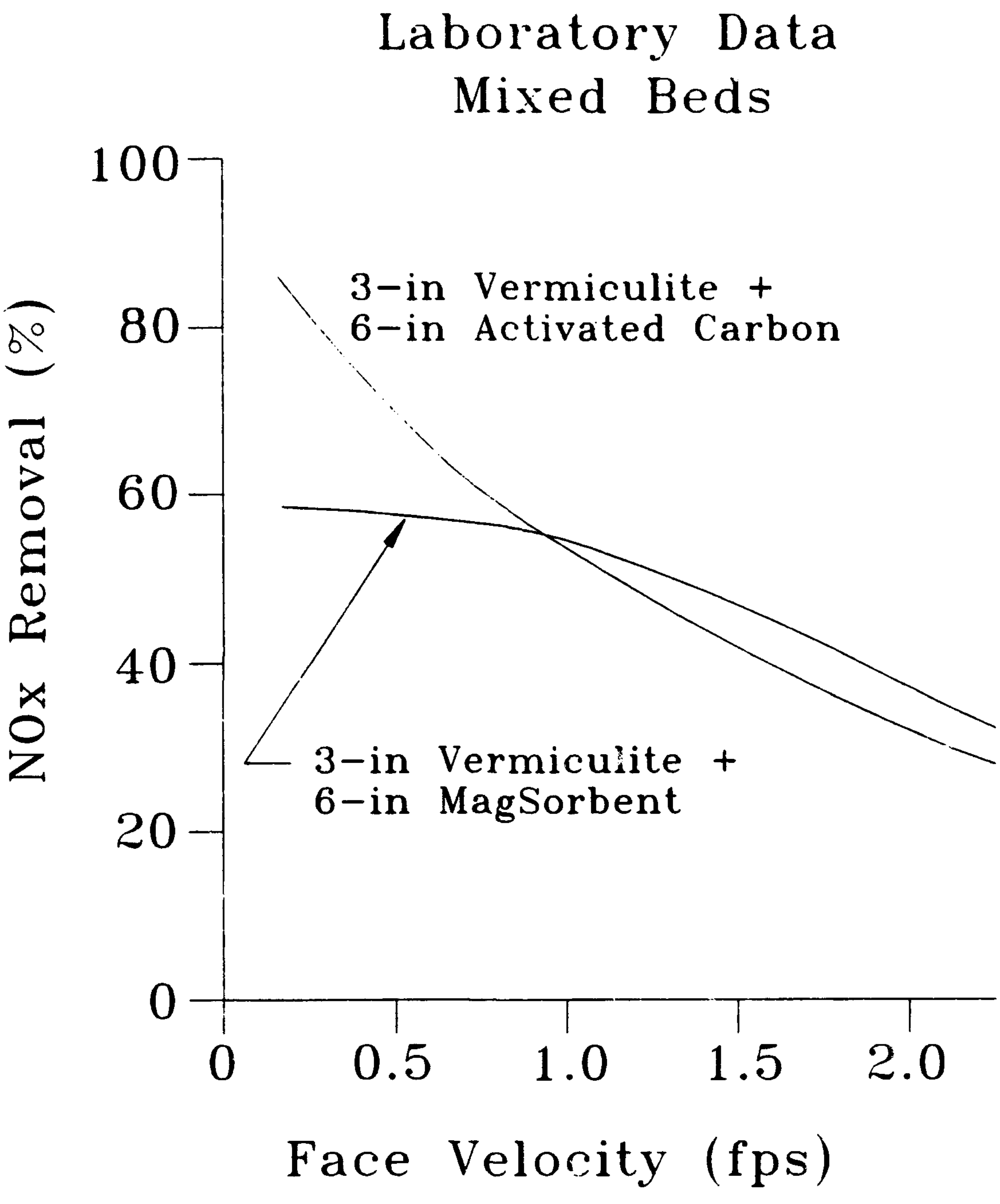

Figure 10. NOx Removal as a Function of Exhaust-Gas Velocity for Two Bed Combinations – Laboratory Data

As might be expected, the pressure drop across the sorbent beds increased with gas velocity and with bed thickness. Gas velocity had the most significant effect on pressure drop. Pressure drops varied roughly in direct proportion with gas velocities. For example, with a gas velocity of 1 fps, the pressure drop was typically 1 in W.G.; with a gas velocity of 3 fps, the drop was about 3 in W.G. Changes in bed thickness for beds up to 9 inches, on the other hand, did not appear to affect pressure drop significantly. Also, bed material type did not appear to affect pressure drop. For a given gas velocity and bed size, beds of vermiculite, MgO–vermiculite and activated carbon all showed about the same pressure drop. Essentially no pressure drop was observed when the system was operated with empty filter bed holders. This showed that the PBFTA itself provided very little back pressure in the system. Pressure drops observed with mixed beds were similar to those seen with single-material beds.

SECTION V

SLIPSTREAM FIELD TESTS

The objective of the slipstream field tests was to determine how filter beds of three sorbent materials, vermiculite, MgO–vermiculite, and activated carbon, perform in removing NOx and CO from actual exhaust gases at McClellan AFB and to collect data that would be useful in designing a full-scale control system for one or more McClellan AFB applications. Three applications planned for study were a large, stationary diesel-fuel-fired engine; a mobile, diesel-fuel-fired electrical generator; and a natural-gas-fired burner-heater.

In this phase of the work, an extensive test program was conducted on exhaust gases from a stationary diesel engine at McClellan AFB, but only a limited number of runs were possible with the mobile diesel unit owing to inclement weather conditions. In addition, McClellan personnel found it impossible to light the burner-heaters after they had been shut down for more than eight months. Additional laboratory runs involving simulated burner-heater exhaust gases therefore were substituted for the planned burner-heater field runs.

A. STATIONARY DIESEL ENGINE RUNS

Of the three stationary diesel-fuel-fired engines at McClellan AFB, the unit employed most extensively (Unit 1) was selected for study. Each stationary diesel engine at McClellan possesses its own exhaust system. Exhaust gases from each engine pass through steel pipe, which first crosses the engine room horizontally and then extends through the side of the building. After passing through the side wall, each exhaust pipe turns upward and connects with an expanded muffler chamber. Following the muffler chamber, the exhaust pipe extends beyond the roof top. A metal rain cap exists at the top end of each exhaust pipe. Figure 11 shows the exhaust system for one unit outside the stationary diesel engine building (Building 262). Prior to the slipstream field tests, McClellan AFB personnel removed the rain cap from Unit 1, permitting easy access to the exhaust gas stream.

Components of the panel-bed-filter test apparatus (PBFTA) were hoisted to the roof of the stationary diesel engine building and there they were assembled. Individual sorbent beds were prepared and were inserted into the filter unit. In Figure 12 are shown 6-inch and 3-inch beds of Mgo–vermiculite or MagSorbent (front) and activated carbon (back). A research engineer installing two filter beds is shown in Figure 13.

A total of 64 runs were performed using different sorbent bed combinations, different bed sizes, and different operating conditions. The data collected during these runs and calculated removal rates are tabulated in Appendix C. The photograph in Figure 14 shows the experimental set-up during a typical run.

B. OTHER PROJECT RUNS

Following the stationary diesel engine runs, the PBFTA was disassembled and its components were removed from the roof of Building 262 and were transported to the parking lot of Building 684. The mobile diesel generator shown in the forefront in Figure 1 was then moved to the same parking lot site. Shortly after the PBFTA was reassembled, the apparatus was connected to

Figure 11. Stationary Diesel-Engine Exhaust System Outside Building 262

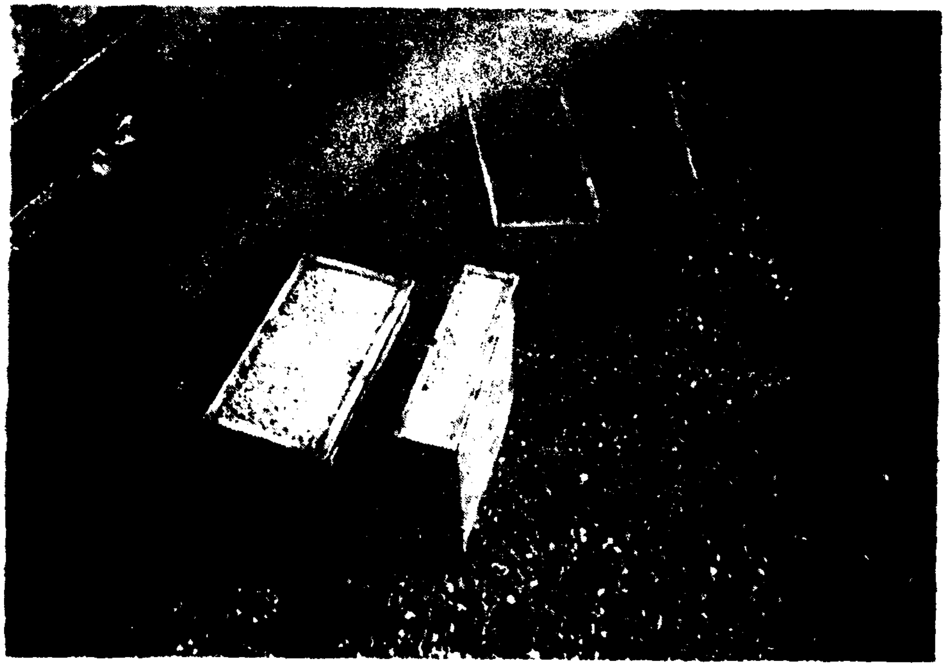

Figure 12. Beds of MagSorbent (Front) and Activated Carbon (Rear)

Figure 13. Preparing the Filter Vessel for a Slipstream Run

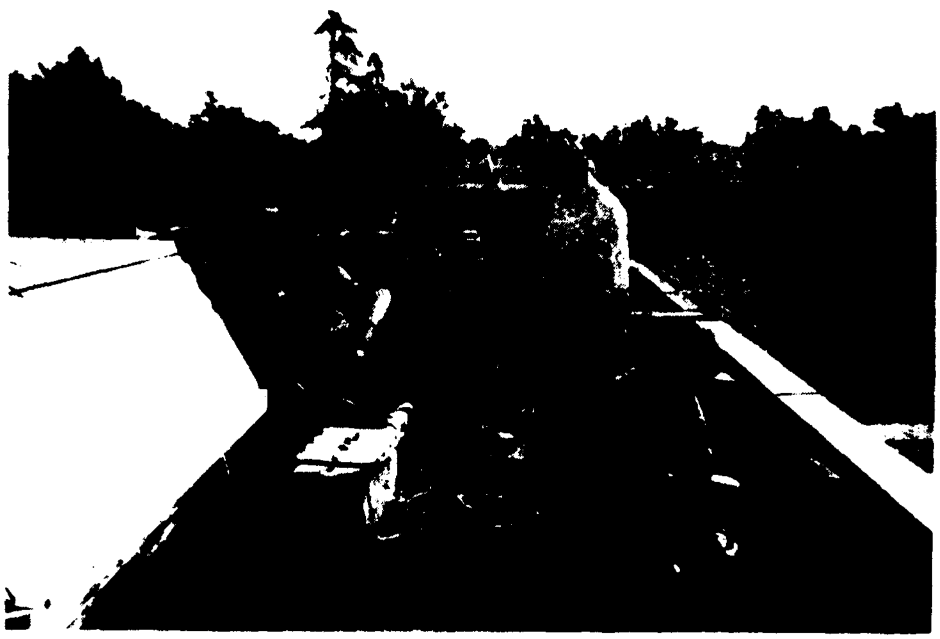

Figure 14. Conducting a Run on Stationary Diesel-Engine Exhaust Gas

the generator exhaust, the generator was turned on, and test runs were begun, a large storm began. Heavy rains continued for nearly a day. After the rains subsided, several runs were performed using the test apparatus arrangement shown in Figure 15.

Although runs on the roof of Building 262 were carried out with no major problems, this was not the case for runs with the mobile unit. The analysis equipment did not perform well, and the data collected were considered less reliable. Also, temperatures and flow rates varied erratically. The exhaust gases emanating from the mobile unit appeared almost supersaturated with moisture. The atmospheric relative humidity during the days of testing was nearly 100 percent. Water readily condensed from the exhaust gases inside the filter beds during all mobile diesel generator runs, and streams of water flowed out from the bottom of the beds. This did not occur during stationary diesel engine runs.

Assembling the PBFTA for burner-heater slipstream tests was easily accomplished. Although the burner-heaters are located high above the ground (See Figure 16), sufficient scaffolding and lift equipment were available to make installation and testing relatively easy. Figure 17 shows the attachment of the PBFTA to a burner-heater unit. Unfortunately, as mentioned earlier, the units could not be turned on, so testing activities were aborted.

Earlier characterizations of the burner-heater exhaust gases by Acurex Corporation provided typical gas compositions. These gas compositions were simulated in the laboratory by burning propane in a special combustor and making additions to the combustion gas stream. It was found possible to simulate the composition and temperature of the exhaust gas fairly well, but not the gas face velocity (flow rate). A high flow rate was required to maintain a flame in the combustor. This high flow rate or velocity was an order of magnitude more than that observed in the actual burner-heaters. Moreover, with the tests that were performed in the laboratory, only 3-inch sorbent beds were employed because only a small filter was visualized as needed for burner-heater applications since only small NOx removals are required. Although some 3-inch beds showed promise in the runs that were performed, in retrospect after examining the collected data, it appears that 6-inch beds should also have been investigated. The data are summarized in Appendix C.

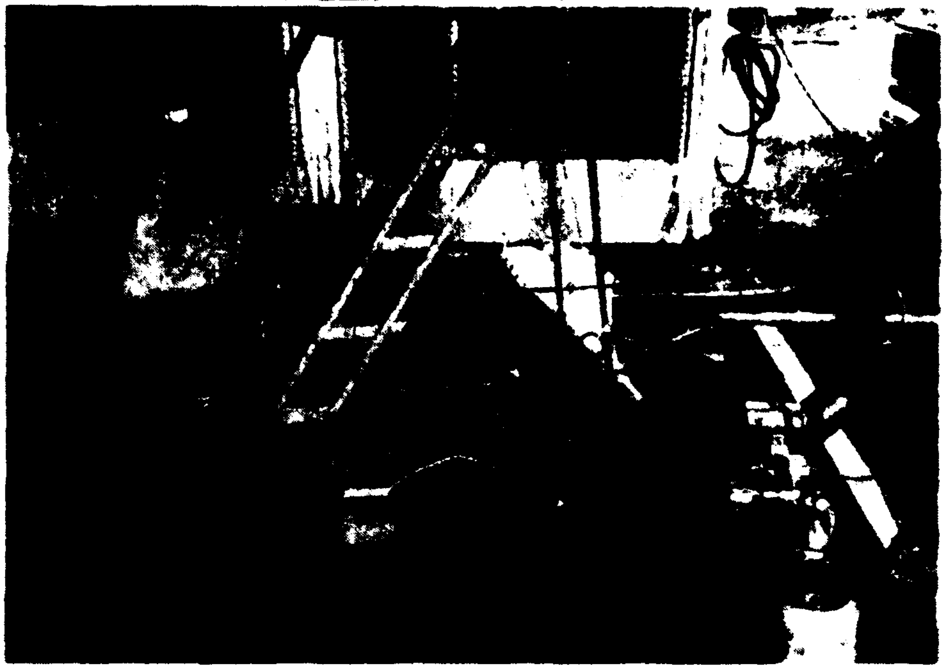

Figure 15. Preparing the Slipstream System for a Mobile Diesel-Generator Exhaust-Gas Run

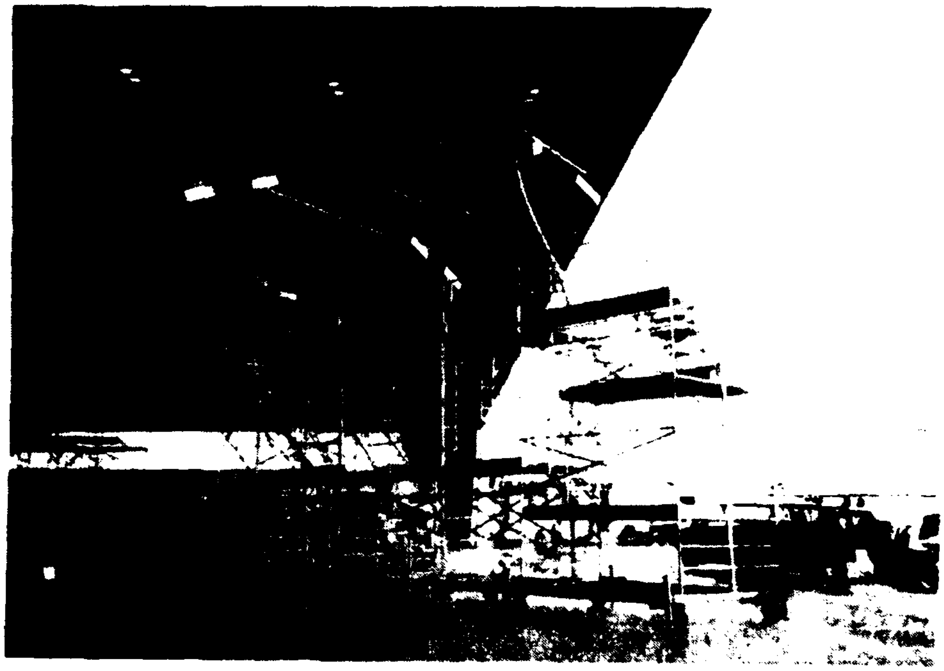

Figure 16. View of the Inside of Building 375

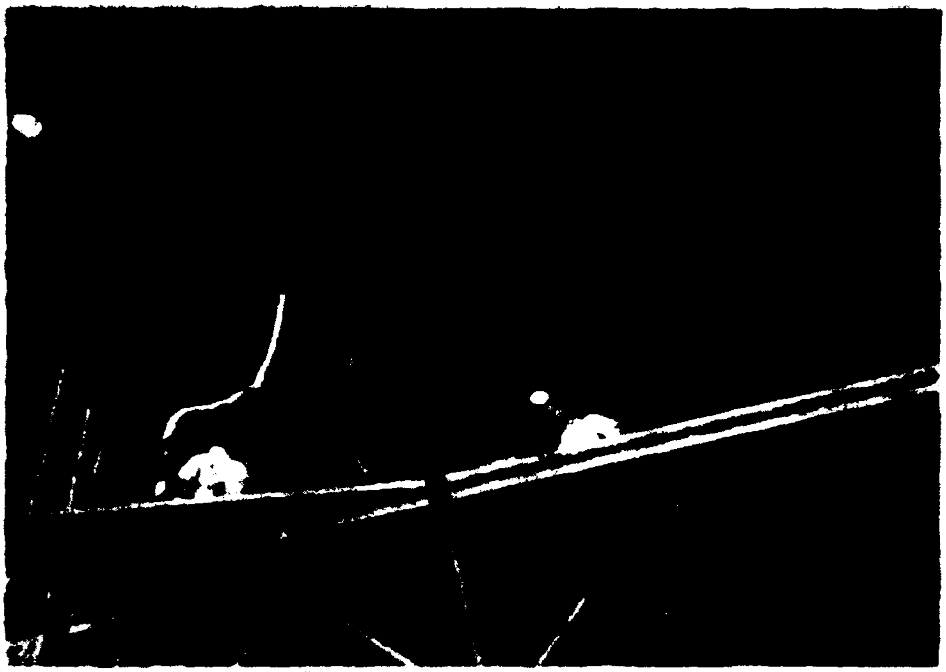

Figure 17. Preparing for a Run on Burner-Heater Exhaust Gases

SECTION VI

DISCUSSION OF RESULTS

The initial laboratory runs were performed at room temperature (approximately 70°F) with air streams into which measured quantities of NO and CO were introduced. The field runs were performed on actual exhaust gases produced by various combustion sources. The temperature of the exhaust gases in the field runs generally ranged from 200° to 400°F. It is not surprising that the results observed in field tests differed somewhat from those seen in the laboratory, although the differences in some cases were very small.

A. VERMICULITE BEDS

In laboratory and field tests, vermiculite beds removed only limited amounts of NOx from gas streams. This was especially true when gas velocities were higher than 1.0 fps. Figure 18 shows NOx removals as a function of face velocity for stationary diesel engine runs. In the laboratory, removals were in the range of 0 to about 15 percent with gas velocities above 1.0 fps. In field tests, they were in the range of 0 to 7.7 percent. NOx removal performance invariably increased with a decrease in face velocity. With a gas velocity of 0.3 fps in the laboratory, for example, about 37 percent NOx removal occurred during a run with a 6-inch vermiculite bed. With low face velocities in the field, NOx removals in the range of 6 to 11 percent were common. The amount of NOx removed increased with bed thickness. Beds of 9 inches removed more NOx than beds of 6 inches.

The vermiculite beds did not remove significant amounts of CO from the gas streams. They did, however, remove most small carbon soot particles that were present in diesel-fuel gas streams. Particulate removals were obvious from visual observations of the gas streams before and after the filters and from visual examinations of the vermiculite beds before and after each run.

The results of the runs with vermiculite beds suggested that the use of vermiculite alone to control NOx is probably not practical; NOx removals are too small. The use of vermiculite in front of a second bed of a more sorbent or catalytic material, on the other hand, could be very attractive. Vermiculite's abilities to capture particulates and to uniformly disperse and distribute an incoming gas, while capturing or removing a limited amount of the NOx itself, could be useful in multiple-bed systems.

B. MgO–VERMICULITE BEDS

Both in laboratory and in field tests, MgO–vermiculite beds performed better than beds of vermiculite alone. Figures 8 and 19 show NOx removal data obtained during laboratory runs and during field runs with stationary diesel-engine exhaust gases. As with vermiculite beds, NOx removal with MgO–vermiculite beds increased with decreases in gas face velocity and with increases in bed thickness.

A comparison of the data in Figure 19 with data in Figure 8 shows that NOx removal performance appeared to be less affected by bed size in field tests than in laboratory tests. The reason for this is not clear.

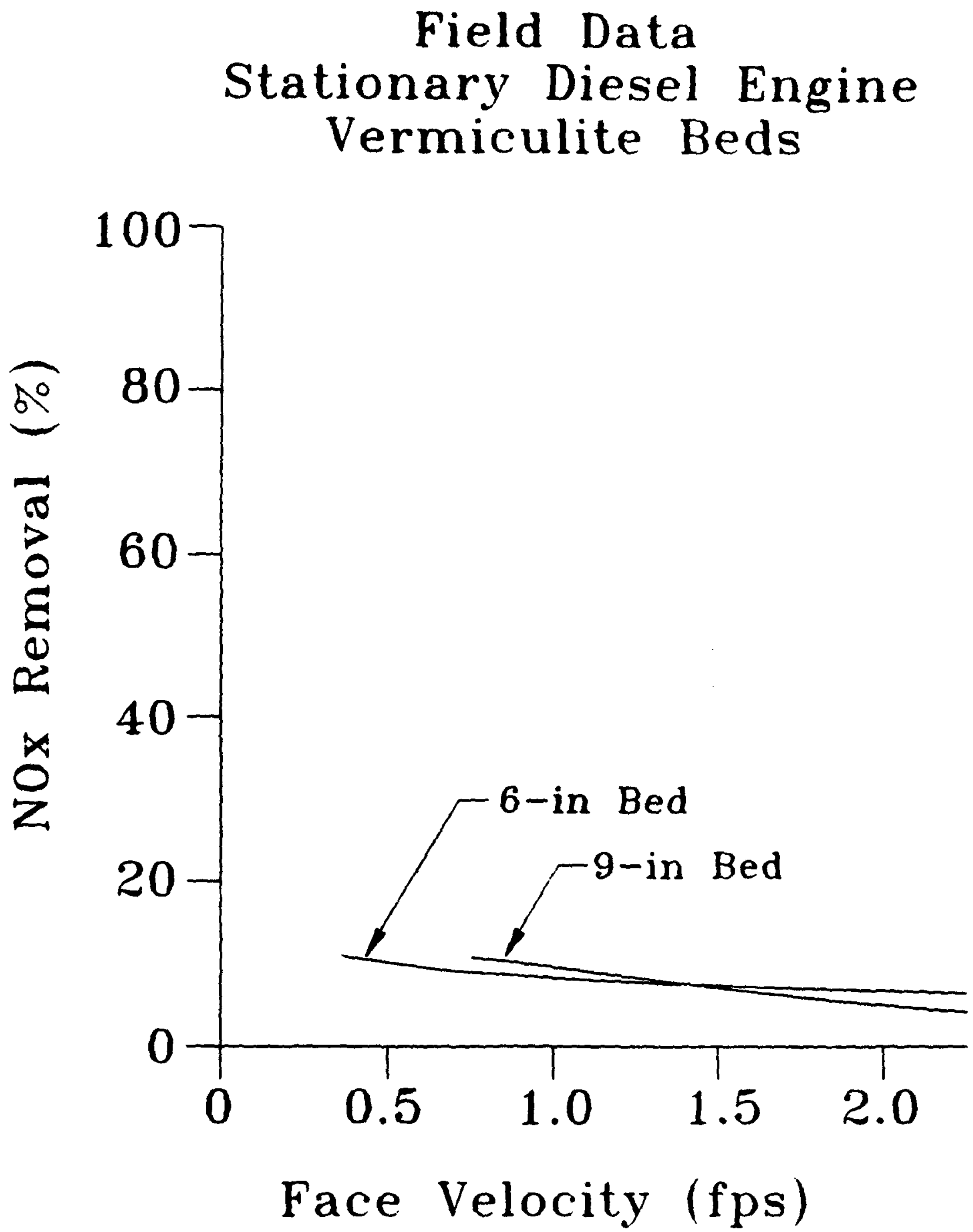

Figure 18. NOx Removal Versus Exhaust-Gas Velocity for Vermiculite Beds in Stationary Diesel Engine Runs

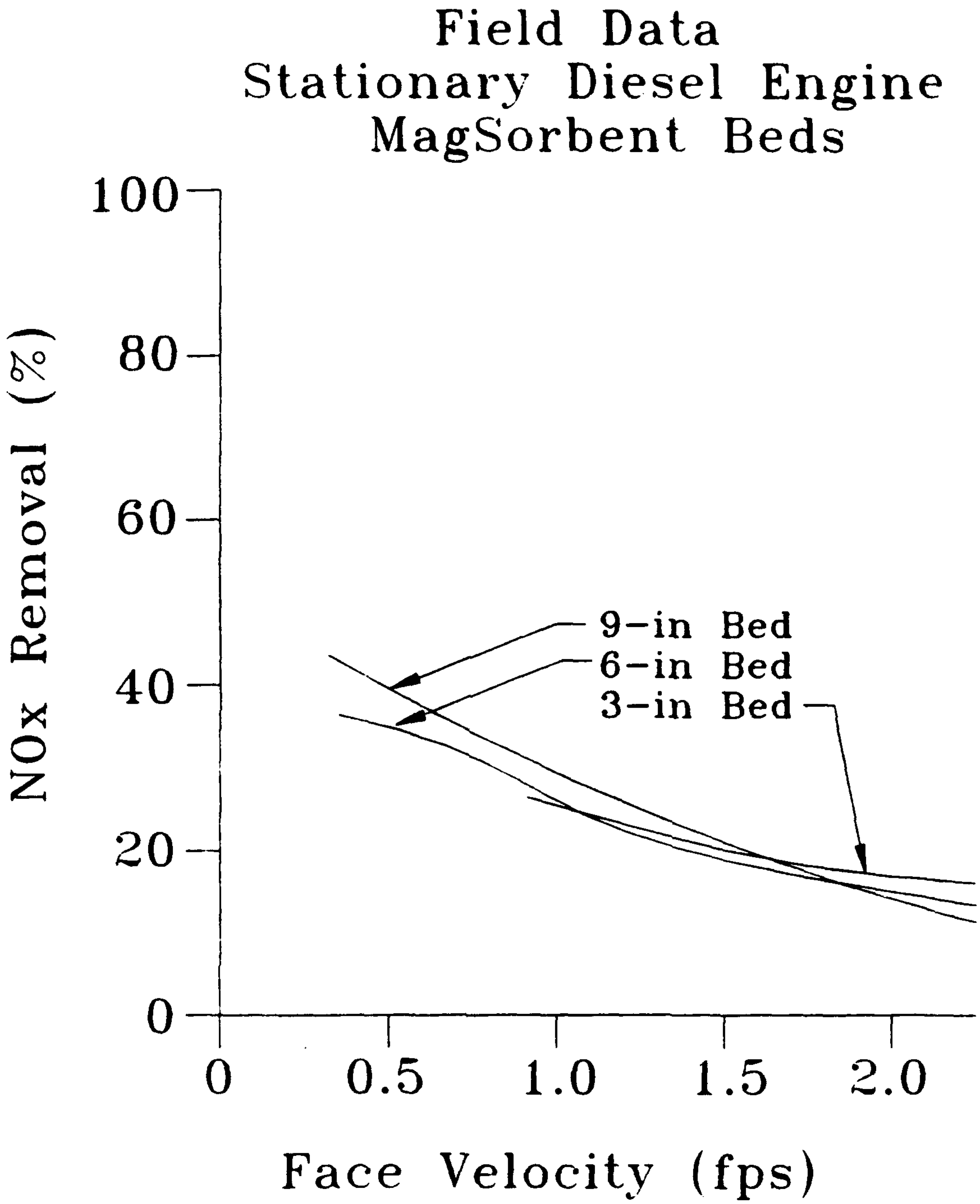

Figure 19. NOx Removal Versus Exhaust-Gas Velocity for MgO–Vermiculite (MagSorbent) Beds in Stationary Diesel Engine Runs

Typically, a 6-inch bed of MgO–vermiculite removed approximately 30 percent of the NOx present in the exhaust gas from the stationary diesel engine at 1.0 fps. A similar bed under similar conditions removed about 35 percent of the NOx in laboratory runs. These removals are in the same range as NOx removals observed in earlier pilot plant runs conducted by Sorbtech engineers at Ohio Edison's Edgewater power plant in Lorain, Ohio on coal-fired boiler exhaust gases.* In Edgewater tests, a 12-inch bed of MgO–vermiculite was employed on an exhaust gas stream of 1.0 to 2.0 fps primarily to remove SO_2.

Thin (3-inch thick) beds of MgO–vermiculite were not particularly effective in reducing the NOx levels in simulated burner-heater exhaust gases at high face velocities (above 1.4 fps). The collected data, however, were not out of line with data obtained in other runs.

The burner-heaters in actual operation produce exhaust gases with relatively low face velocities. A control device for a burner-heater would be expected to see an exhaust gas face velocity of about 0.25 fps. With this low face velocity, a 3-inch MgO–vermiculite filter might be expected to remove 30 to 35 percent of the NOx present, based on the results of laboratory and field tests.

Beds of MgO–vermiculite appeared to be somewhat effective in removing CO from exhaust gases at low space velocities (below 1.0 fps), but not at high space velocities. Beds of MgO–vermiculite also appeared to be effective in removing soot particles from exhaust gases, but not as effective as vermiculite alone. In essentially all MgO–vermiculite runs, percent NO_2 removals were higher than percent NO removals. Ammonia additions to gas streams in MgO–vermiculite-bed runs did not markedly improve NOx removals.

C. ACTIVATED CARBON BEDS

Data collected during activated-carbon-bed runs on stationary diesel-engine exhaust gases are shown plotted in Figure 20. A comparison of these data with those shown in Figure 9 for laboratory runs showed field NOx removals about half those observed in the laboratory for gas velocities above 1.0 fps. For 6-inch beds at 0.5 fps, however, NOx removal rates were very similar (60 to 65 percent).

The field runs performed clearly demonstrated that two variables can significantly affect NOx removal performance. The first is moisture content of the exhaust gas. If the gas is saturated with water and cools appreciably while passing through the activated carbon bed, water condenses on the individual activated carbon particles and destroys the ability of the sorbent to remove NOx. As long as the moisture remains in gaseous or vapor form, moisture does not appear to be a problem. The second is temperature. It is well known that activated carbon's ability to physically sorb most liquid and gaseous substances decreases with temperature. This appears to be the case for NOx, at least at temperatures above 300°F.

Except at low gas velocities, activated carbon did not demonstrate the ability to remove CO in field tests. In fact, in a number of runs, the CO levels of the gases exiting the filters exceeded the CO levels of the entering gases.

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*S. G. Nelson, "Sanitech's 2.5 MWe Magnesia Dry Scrubbing Demonstration Project," Joint EPRI/EPA/DOE 1991 SO_2 Control Symposium, Washington, D.C., December, 1991.

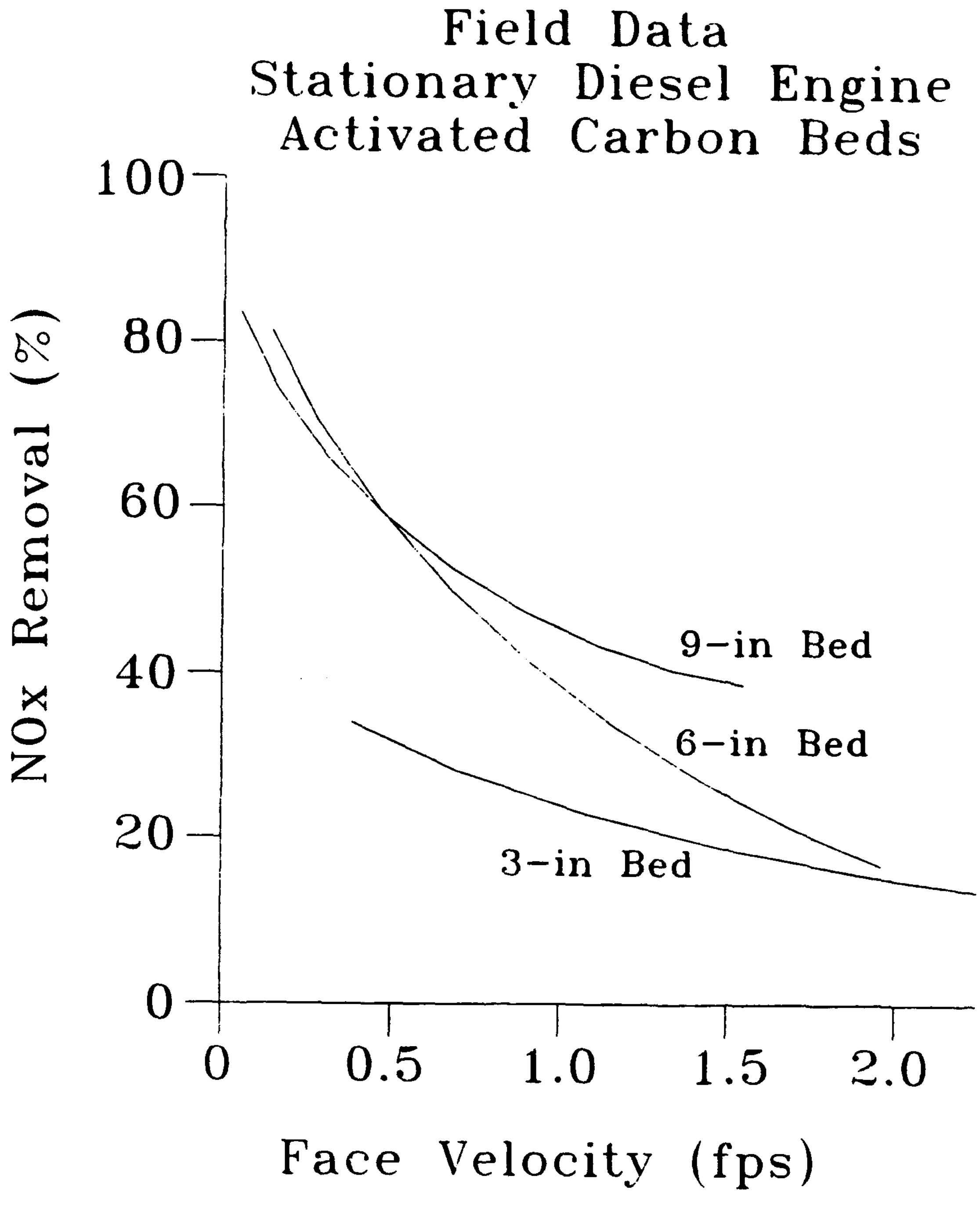

Figure 20. NOx Removal Versus Exhaust-Gas Velocity for Activated Carbon Beds in Stationary Diesel Engine Runs

Unusual results were also observed when ammonia additions were made to the exhaust gases during the activated-carbon-bed runs. Actual increases in NOx levels occurred. Whether these increases were real or not is not known. It is suspected that the addition of high levels of ammonia to the system affected the chemical analysis equipment being employed. In reality, all data collected during runs involving ammonia are believed to be questionable.

Activated carbon was observed to effectively remove both NO and NO_2.

D. COMBINATION BEDS

In laboratory runs, a combination of beds of 3 inches of vermiculite and 6 inches of activated carbon demonstrated very promising NOx removals. NOx removal rates above 60 percent were common. In field tests with stationary diesel-engine exhaust gases, almost identical results were obtained with the same bed combination.

Good results were also observed with a combination of beds of 3 inches of vermiculite and 6 inches of MgO–vermiculite (MagSorbent) at low face velocities. However, NOx removals fell off rapidly at velocities above 1.0 fps. A combination bed of MagSorbent and activated carbon showed performances between those of vermiculite–activated carbon and vermiculite–MagSorbent. The results of runs with the different combinations beds are shown in Figure 21.

The combination beds containing vermiculite were effective in removing soot particles from exhaust gases. They appeared to be also slightly more effective than single beds alone in reducing CO levels in the exhaust gases. Combination beds removed both NO and NO_2 effectively, although like single component filters, NO_2 removals were slightly better than NO removals. Combination beds with activated carbon did not perform well in stationary diesel-generator runs after the beds became saturated with condensed water.

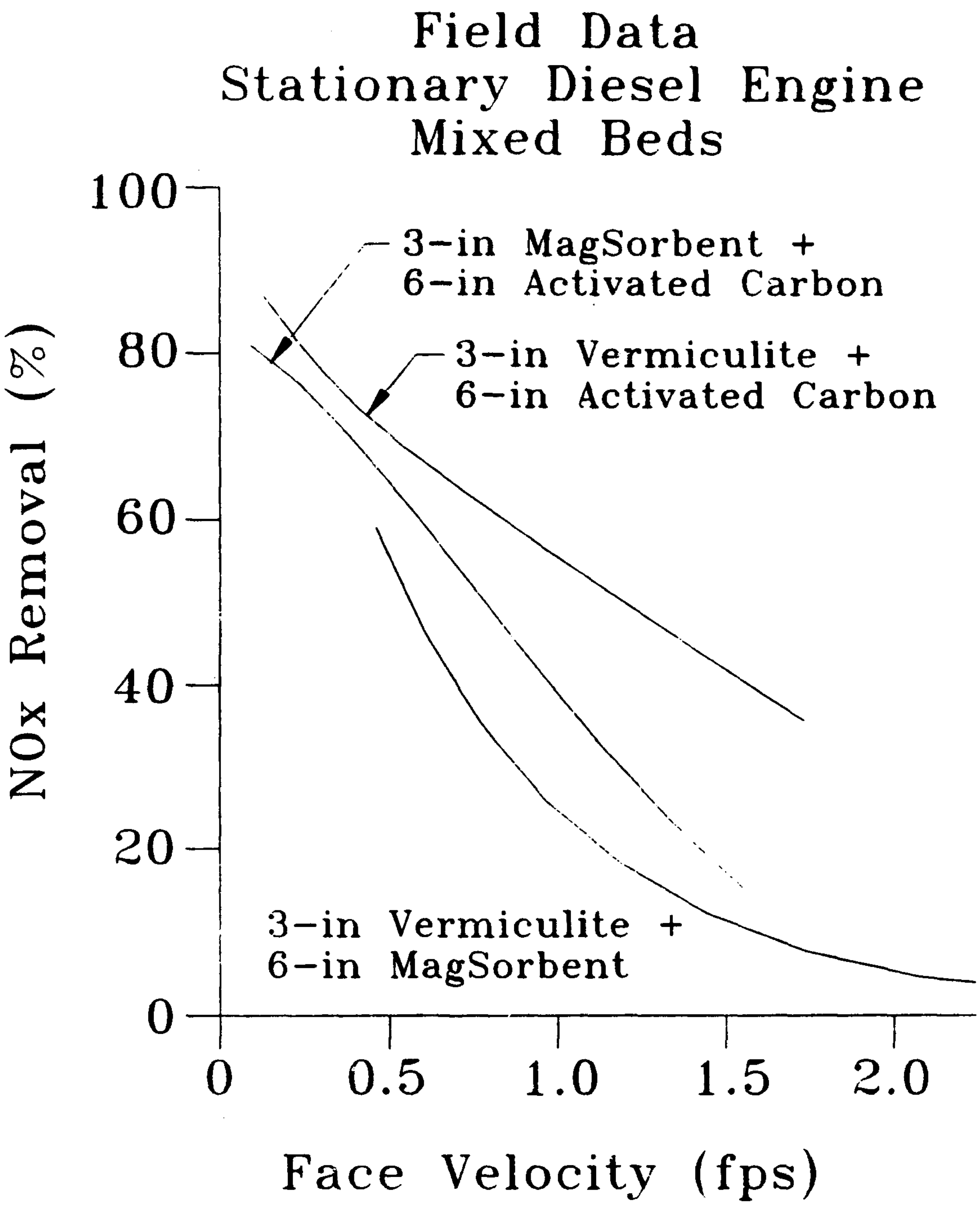

Figure 21. NOx Removal Versus Exhaust-Gas Velocity for Three Bed Combinations in Stationary Diesel Engine Runs

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

Promising results were obtained in the SBIR Phase I project. The new technology developed earlier for jet-engine test cells appears to be applicable to other combustion systems at McClellan AFB and at other Air Force sites.

A. CONCLUSIONS

Based on the project results, the following conclusions were made:

1. Of the three McClellan AFB applications examined (stationary diesel engines, mobile diesel generators, and natural gas burner-heaters), the stationary diesel-engine application appears to be the most promising one for significant NOx reductions.

2. The stationary diesel engines were observed to be one of the largest producers and emitters of NOx at McClellan AFB.

3. A second promising McClellan AFB application of the new technology is the natural gas burner-heaters that are employed for drying repainted aircraft. These units, which are currently shut down owing to high NOx levels, require only a small reduction in NOx to meet current NOx standards.

4. The new technology may also be applicable to the third combustion system examined at McClellan AFB, mobile diesel generators. However, additional research is needed to reduce or accommodate the high levels of moisture typically present in the exhaust gases from these units to make the new technology applicable.

5. Of the three bed materials (vermiculite, MgO–vermiculite, and activated carbon) examined in the project for NOx control, activated carbon and MgO–vermiculite demonstrated the most promise. NOx removals with vermiculite alone were small. Of the three bed materials examined for the control of small particulates (soot), vermiculite showed the most promise.

6. A system showing the greatest promise for combined control of NOx and small particulates for the stationary diesel-engine application consists of two beds in series, a vermiculite bed followed by an activated carbon bed.

7. A promising system for NOx control for McClellan AFB's burner-heaters is one consisting of a simple MgO–vermiculite filter. A similar filter, but prefaced by a thin bed of vermiculite, may be suitable for combined NOx-particulates control for mobile diesel units.

8. Slipstream test results in the field, although the exhaust-gas conditions were different, showed the same general trends as laboratory test results.

9. The velocity of the exhaust gas was one of the most important variables affecting NOx removal performance. NOx removals decreased with increases in exhaust gas face velocity. Total bed thickness was also an important variable. NOx removals generally increased with increases in total bed thickness.

10. All three materials examined removed both NO_2 and NO. In nearly all cases, percentage NO_2 reductions were larger than percentage NO reductions.

11. All three materials removed at least small amounts of carbon monoxide (CO), in addition to NOx. Like NOx, CO removal was a strong function of the face velocity of the exhaust gas. Of the three materials examined, MgO–vermiculite appeared to demonstrate the highest CO removals.

12. Ammonia additions to the exhaust gases improved NOx removals in some cases, but the improvements seen did not appear to be large enough to justify their use. Ammonia slippage through the sorbent beds occurred in all test runs with ammonia additions.

B. RECOMMENDATIONS

Sorbent Technologies Corporation recommends that the research initiated in Phase I be carried forward. More specifically it recommends that

1. Small prototype control systems, suitable for treating entire combustion-unit exhaust gas streams, be designed, built and installed at McClellan AFB to examine the new technology in no fewer than four applications.

2. These applications should include, but should not be limited to, the stationary diesel engines; the natural-gas burner-heaters; mobile units, such as automobiles, trucks, regenerators, or cranes; and an incinerator.

3. Prototype runs should be performed to collect data relating to the useful working lives of the bed materials and to develop procedures for regenerating and reusing the bed materials.

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APPENDIX A

EQUIPMENT DRAWINGS

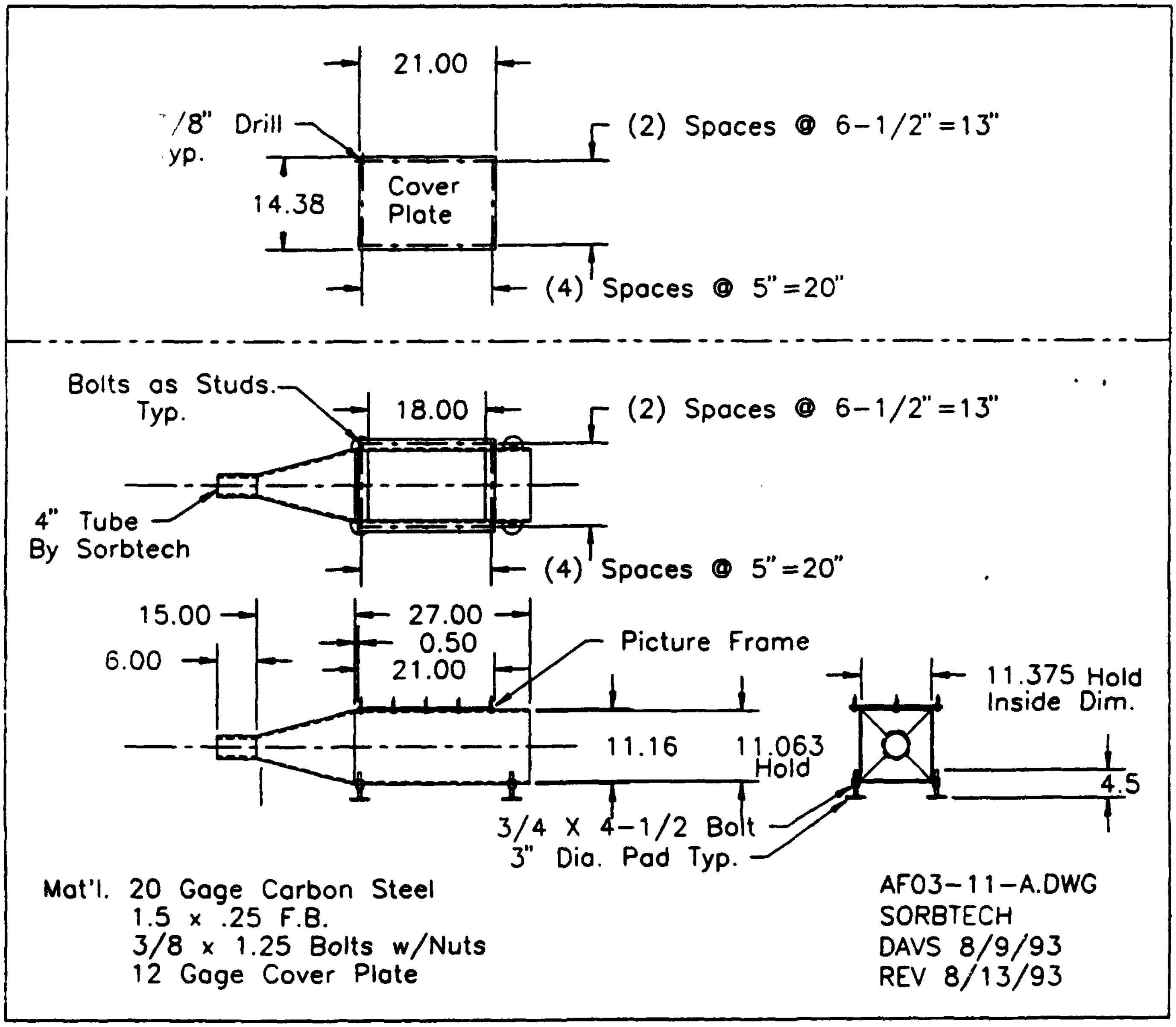

Exhibit A-1. Drawing of Filter Vessel

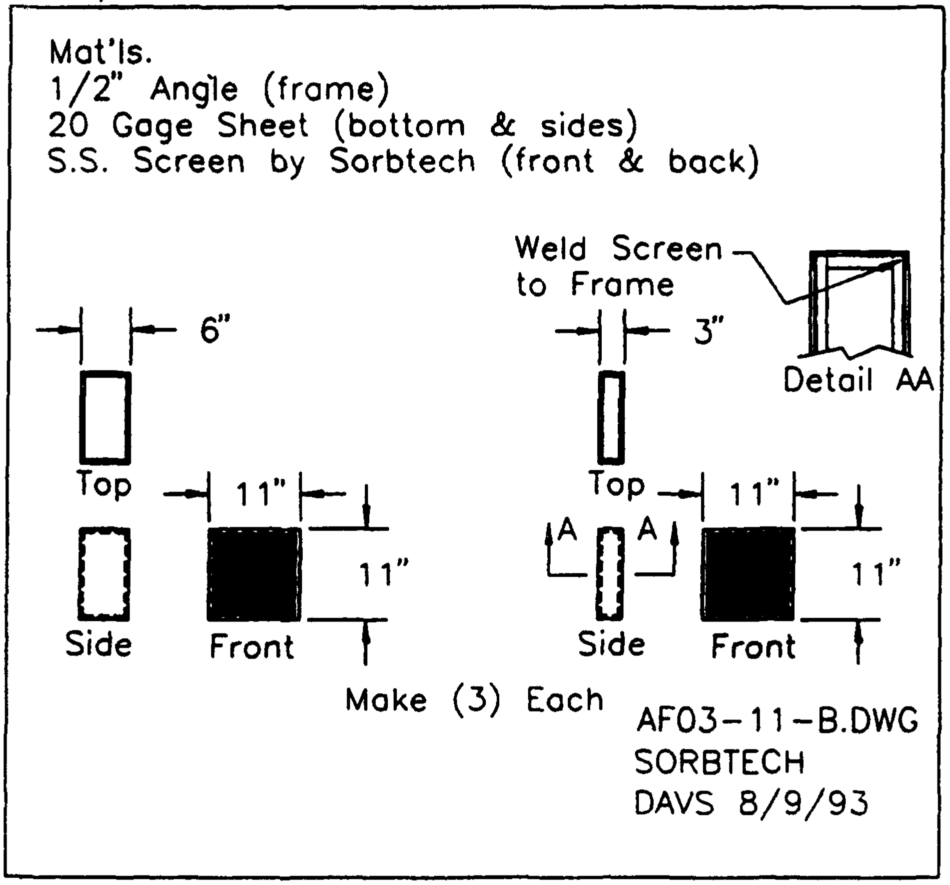

Exhibit A-2. Drawings of Sorbent Holders

APPENDIX B

LABORATORY DATA

APPENDIX B.

TABLE B-1. LABORATORY TEST RESULTS

PHASE ONE

Bed Combination	Fan Setting	Measured ΔP (In. H_2O)	Measured Velocity Duct. (fpm)	Measured NOx In (ppm)	Measured NOx Out (ppm)	Calculated ΔNOx (%)	Calculated Velocity Bed. (fps)
3" MagSorbent + 6" MagSorbent	30	0.20	80	23	9	60.9	0.15
(9" Total)	50	0.95	425	9	6	33.3	0.77
(9" Total)	80	3.60	1000	12	9	25.0	1.82
(9" Total)	100	5.50	1400	12	9	25.0	2.55
6" MagSorbent	30	0.15	190	42	23	45.2	0.35
(6" Total)	50	0.85	725	17	12	29.4	1.32
(6" Total)	80	3.60	1800	9	9	0.0	3.28
(6" Total)	100	5.30	2300	20	19	5.0	4.19
3" MagSorbent	30	0.10	140	82	55	32.9	0.25
(3" Total)	50	1.00	800	26	23	11.5	1.46
(3" Total)	80	3.60	2100	45	45	0.0	3.82
(3" Total)	100	5.00	2600	42	42	0.0	4.73
3" Activated Carbon							
+ 6" Activated Carbon	30	0.10	58	165	14.5	91.2	0.11
(9" Total)	50	0.90	350	44	10	77.3	0.64
(9" Total)	80	3.70	900	59	24	59.3	1.64
(9" Total)	100	5.60	1200	65	31	52.3	2.18
6" Activated Carbon	30	0.10	90	96.5	22	77.2	0.16
(6" Total)	50	1.00	530	69	34	50.7	0.96
(6" Total)	80	3.60	1300	57	42	26.3	2.37
(6" Total)	100	5.30	1800	56	43	23.2	3.28
3" Activated Carbon	30	0.10	125	171	68	60.2	0.23
(3" Total)	50	0.90	725	43	35	18.6	1.32
(3" Total)	80	3.00	2000	43	40	7.0	3.64
(3" Total)	100	4.90	2450	46	40	13.0	4.46
3" Activated Carbon + 3" Activated Carbon (fill)							
+ 6" Activated Carbon	30	0.10	35	155	7	95.5	0.06
(12" Total)	50	1.00	250	34	4	88.2	0.45
(12" Total)	80	4.30	700	64	31	51.6	1.27
(12" Total)	100	5.90	890	92	38	58.7	1.62

TABLE B-1. LABORATORY TEST RESULTS

PHASE ONE - Continued

		Measured				Calculated	
Bed Combination	Fan Setting	ΔP (In. H_2O)	Velocity Duct (fpm)	NOx In (ppm)	NOx Out (ppm)	ΔNOx (%)	Velocity Bed (fps)
3" Vermiculite + 6" Vermiculite	30	0.10	110	95	67	29.5	0.20
(9" Total)	50	0.90	700	26.5	23.5	11.3	1.27
(9" Total)	80	3.50	1900	43	40	7.5	3.46
(9" Total)	100	4.50	2250	40	39	2.5	4.09
6" Vermiculite	30	0.15	180	130	82	36.9	0.33
(6" Total)	50	0.80	950	40	38	5.0	1.73
(6" Total)	80	3.10	2400	34	33	2.9	4.37
(6" Total)	100	4.50	3100	34	34	0.0	5.64
3" Vermiculite	30	0.10	350	133	120	9.8	0.64
(3" Total)	50	0.80	1350	41	40	2.5	2.46
(3" Total)	80	2.80	3100	34	33	2.5	5.64
(3" Total)	100	3.90	3800	37	37	0.0	6.92

TABLE B-2. LABORATORY TEST RESULTS

PHASE TWO

				Measured				Calculated		
Bed Combination	Fan Setting	ΔP (In. H_2O)	Velocity Duct. (fpm)	NOx In (ppm)	NOx Out (ppm)	CO In (ppm)	CO Out (ppm)	ΔNOx (%)	ΔCO (%)	Velocity Bed(fps)
3" Vermiculite + 6" Activated Carbon	30	0.10	75	225	33	–	–	85.3	–	0.14
3" Vermiculite + 6" Activated Carbon	50	1.00	425	57	24	–	–	57.9	–	0.77
3" Vermiculite + 6" Activated Carbon	80	3.80	1000	66	44	–	–	33.3	–	1.82
3" Vermiculite + 6" Activated Carbon	100	5.50	1400	66	50	–	–	24.2	–	2.55
3" Vermiculite + 6" Activated Carbon	30	0.15	80	136	18	95	54	86.8	43.2	0.15
3" Vermiculite + 6" Activated Carbon	50	1.00	450	40	18	27	24	55.0	11.1	0.82
3" Vermiculite + 6" Activated Carbon	80	3.90	1100	61	45	27	24	26.2	11.1	2.00
3" Vermiculite + 6" Activated Carbon	100	5.50	1475	65	51	27	22	21.5	18.5	2.68
3" Vermiculite + 9" Activated Carbon	30	0.20	15	292	61	152	55	79.1	63.8	0.03
3" Vermiculite + 9" Acitvated Carbon	50	1.10	275	97	24	34	27	75.3	20.6	0.50
3" Vermiculite + 9" Activated Carbon	80	4.20	740	77	45	24	21	41.6	12.5	1.35
3" Vermiculite + 9" Activated Carbon	100	5.80	860	65	45	27	16	30.8	40.7	1.57
3" Vermiculite + 6" MagSorbent	30	0.10	85	224	93	–	–	58.5	–	0.15
3" Vermiculite + 6" MagSorbent	50	1.00	525	69	32	–	–	53.6	–	0.96
3" Vermiculite + 6" MagSorbent	80	3.80	1375	51	39	–	–	23.5	–	2.50
3" Vermiculite + 6" MagSorbent	100	5.40	1750	54	45	–	–	16.7	–	3.18
Empty Filter Beds	30	0.00	800	–	–	–	–	–	–	1.46
Empty Filter Beds	50	0.05	2350	–	–	–	–	–	–	4.28
Empty Filter Beds	80	0.05	5000	–	–	–	–	–	–	9.10
Empty Filter Beds	100	0.05	6000	–	–	–	–	–	–	10.92

APPENDIX C

FIELD-TEST DATA

APPENDIX C.

TABLE C-1
STATIONARY DIESEL ENGINE FIELD TEST RESULTS

Bed Composition	Fan Setting	Temperature (Deg F) In	Temperature (Deg F) Out	dP Across Bed (in H2O)	Duct Velocity (fpm)	NO (ppm) In	NO (ppm) Out	NO2 (ppm) In	NO2 (ppm) Out	NOx (ppm) In	NOx (ppm) Out	% NOx Removal	% NO Removal	% NO2 Removal
3" MagSorbent	30	257	140	0.2	500	539	191	160	40	699	231	66.95	64.56	75.00
3" MagSorbent	50	255	161	0.7	1000	529	400	152	115	681	515	24.38	24.39	24.34
3" MagSorbent	80	273	188	2.3	2250	504	440	147	128	651	568	12.75	12.70	12.93
3" MagSorbent	100	291	219	2.8	2900	490	468	139	139	629	607	3.50	4.49	0.00
6" MagSorbent	0	95	NT	0.2	190	570	400	220	80	790	480	39.24	29.82	63.64
6" MagSorbent	30	255	234	0.5	480	562	410	187	88	749	498	33.51	27.05	52.94
6" MagSorbent	50	215	103	0.9	520	586	502	199	130	785	632	19.49	14.33	34.67
6" MagSorbent	80	238	194	2.8	1400	554	498	179	149	733	647	11.73	10.11	16.76
6" MagSorbent	100	260	228	3.9	1875	535	504	165	152	700	656	6.29	5.79	7.88
9" MagSorbent	30	240	176	0.3	175	535	331	172	48	707	379	46.39	38.13	72.09
9" MagSorbent	50	240	164	1.0	475	542	410	154	73	696	483	30.60	24.35	52.60
9" MagSorbent	80	257	186	3.0	950	525	466	161	127	686	593	13.56	11.24	21.12
9" MagSorbent	100	270	216	4.1	1325	510	470	149	125	659	595	9.71	7.84	16.11
3" Activated Carbon	30	228	122	0.3	210	510	335	129	54	639	389	39.12	34.31	58.14
3" Activated Carbon	50	233	130	0.8	620	580	498	128	76	708	574	18.93	14.14	40.63
3" Activated Carbon	80	264	142	2.8	1450	500	490	100	68	600	558	7.00	2.00	32.00
3" Activated Carbon	100	267	151	3.9	2050	496	481	107	84	603	565	6.30	3.02	21.50
6" Activated Carbon	30	211	117	0.5	75	508	107	126	5	634	112	82.33	78.94	96.03
6" Activated Carbon	50	227	116	1.1	255	514	296	130	31	644	327	49.22	42.41	76.15
6" Activated Carbon	80	260	150	3.4	700	514	438	130	44	644	482	25.16	14.79	66.15
6" Activated Carbon	100	274	140	4.6	1075	500	487	117	54	617	541	12.32	2.60	53.85
9" Activated Carbon	30	200	135	0.5	30	528	106	128	4	656	110	83.23	79.92	96.88
9" Activated Carbon	50	214	122	1.2	160	520	261	131	17	651	278	57.30	49.81	87.02
9" Activated Carbon	80	256	130	3.8	550	528	357	130	26	658	383	41.79	32.39	80.00
9" Activated Carbon	100	262	134	4.7	850	528	384	130	30	658	414	37.08	27.27	76.92
6" Vermiculite	30	225	117	0.2	200	574	520	137	113	711	633	10.97	9.41	17.52
6" Vermiculite	50	248	168	0.8	550	580	550	143	132	723	682	5.67	5.17	7.69
6" Vermiculite	80	282	198	3.2	1800	548	520	110	105	658	625	5.02	5.11	4.55
6" Vermiculite	100	298	248	3.9	2000	547	547	121	116	668	663	0.75	0.00	4.13
9" Vermiculite	30	245	205	0.5	410	585	530	169	126	754	656	13.00	9.40	25.44
9" Vermiculite	50	200	195	1.0	625	585	578	169	123	754	701	7.03	1.20	27.22
9" Vermiculite	80	278	194	3.4	1050	594	584	140	135	734	719	2.04	1.68	3.57
9" Vermiculite	100	296	222	3.6	1525	599	568	144	136	743	704	5.25	5.18	5.56

APPENDIX C.

TABLE C-1
STATIONARY DIESEL ENGINE FIELD TEST RESULTS

Bed Composition	Fan Setting	Temperature (Deg F) In	Temperature (Deg F) Out	dP Across Bed (in H2O)	Duct Velocit (fpm)	CO (ppm) In	CO (ppm) Out	% CO Removal	O2 (%) In	O2 (%) Out	Bed Velocity (fps)	Adj'd* % NOx Removal
3" MagSorbent	30	257	140	0.2	500	181	62	65.75	16.8	19.0	0.91	26.56
3" MagSorbent	50	255	161	0.7	1000	184	167	9.24	16.8	17.2	1.82	15.97
3" MagSorbent	80	273	188	2.3	2250	164	146	10.98	17.1	17.1	4.10	12.75
3" MagSorbent	100	291	219	2.8	2900	170	170	0.00	17.2	17.2	5.28	3.50
6" MagSorbent	0	95	NT	0.2	190	330	274	16.97	16.2	16.4	0.35	36.48
6" MagSorbent	30	255	234	0.5	480	182	132	27.47	16.5	16.6	0.87	31.93
6" MagSorbent	50	215	103	0.9	520	224	222	0.89	16.4	16.4	0.95	19.49
6" MagSorbent	80	238	194	2.8	1400	196	187	4.59	16.7	16.7	2.55	11.73
6" MagSorbent	100	260	228	3.9	1875	172	172	0.00	16.8	16.8	3.41	6.29
9" MagSorbent	30	240	176	0.3	175	186	125	32.80	16.7	16.9	0.32	43.64
9" MagSorbent	50	240	164	1.0	475	177	177	0.00	16.6	16.6	0.86	30.60
9" MagSorbent	80	257	186	3.0	950	179	162	9.50	16.9	16.8	1.73	15.72
9" MagSorbent	100	270	216	4.1	1325	168	166	1.19	17.0	17.0	2.41	9.71
3" Activated Carbon	30	228	122	0.3	210	170	142	16.47	16.9	17.2	0.38	34.05
3" Activated Carbon	50	233	130	0.8	620	180	144	20.00	16.5	16.6	1.13	17.00
3" Activated Carbon	80	264	142	2.8	1450	121	117	3.31	17.2	17.1	2.64	9.51
3" Activated Carbon	100	267	151	3.9	2050	109	119	-9.17	17.4	17.3	3.73	8.98
6" Activated Carbon	30	211	117	0.5	75	148	126	14.86	16.7	16.9	0.14	81.43
6" Activated Carbon	50	227	116	1.1	255	158	164	-3.80	16.8	16.7	0.46	50.46
6" Activated Carbon	80	260	150	3.4	700	158	168	-6.33	16.8	16.7	1.27	26.98
6" Activated Carbon	100	274	140	4.6	1075	154	154	3.00	16.9	16.7	1.96	16.59
9" Activated Carbon	30	200	135	0.5	30	158	103	34.81	16.8	16.7	0.05	83.64
9" Activated Carbon	50	214	122	1.2	160	167	167	0.00	16.8	16.8	0.29	57.30
9" Activated Carbon	80	256	130	3.8	550	168	168	0.00	16.8	16.8	1.00	41.79
9" Activated Carbon	100	262	134	4.7	850	167	157	5.99	16.8	16.7	1.55	38.62
6" Vermiculite	30	225	117	0.2	200	130	117	10.00	16.5	16.5	0.36	10.97
6" Vermiculite	50	248	168	0.8	550	130	130	0.00	16.5	16.5	1.00	5.67
6" Vermiculite	80	282	198	3.2	1800	111	111	0.00	17.0	16.9	3.28	7.45
6" Vermiculite	100	298	248	3.9	2000	124	121	2.42	16.9	16.8	3.64	3.23
9" Vermiculite	30	245	205	0.5	410	130	128	1.54	16.6	16.7	0.75	10.88
9" Vermiculite	50	200	195	1.0	625	135	135	0.00	16.6	16.5	1.14	9.19
9" Vermiculite	80	278	194	3.4	1050	138	130	5.80	16.5	16.4	1.91	4.27
9" Vermiculite	100	296	222	3.6	1525	133	133	0.00	16.4	16.5	2.78	3.05

* NOx removals based on the assumptions that some air leakage or dilution occurred in the system and that the O_2 level of exhaust gas did not change upon passing through the filters.

TABLE C-1 (CONTINUED)
STATIONARY DIESEL ENGINE FIELD TEST RESULTS

Bed Composition	Fan Setting	Temperature (Deg F) In	Temperature (Deg F) Out	dP Across Bed (in H2O)	Duct Velocity (fpm)	NO (ppm) In	NO (ppm) Out	NO2 (ppm) In	NO2 (ppm) Out	NOx (ppm) In	NOx (ppm) Out	% NOx Removal	% NO Removal	% NO2 Removal
3" Vermiculite + 6" Act Carbon	30	186	91	0.5	70	517	80	138	6	655	86	86.87	84.53	95.65
3" Vermiculite + 6" Act Carbon	50	211	102	1.1	225	520	180	135	8	655	188	71.30	65.38	94.07
3" Vermiculite + 6" Act Carbon	80	252	125	3.4	650	522	162	138	40	660	202	69.39	68.97	71.01
3" Vermiculite + 6" Act Carbon	100	266	144	5.4	950	524	390	140	38	664	428	35.54	25.57	72.86
3" Vermiculite + 6" MagSorbent	30	284	255	0.3	250	1200	475	338	107	1538	582	62.16	60.42	68.34
3" Vermiculite + 6" MagSorbent	50	298	245	0.8	450	1210	920	288	202	1498	1122	25.10	23.97	29.86
3" Vermiculite + 6" MagSorbent	80	348	204	3.0	750	1200	1150	292	260	1492	1410	5.50	4.17	10.96
3" Vermiculite + 6" MagSorbent	100	374	252	3.7	1350	1200	1155	292	292	1492	1447	3.02	3.75	0.00
9" MagSorbent	50	235	170	1.0	490	539	508	154	140	693	648	6.49	5.75	9.09
9" MagSorbent + NH3	50	245	194	1.0	490	550	505	133	108	683	613	10.25	8.18	18.80 (1)
9" MagSorbent + NH3	100	262	200	3.9	1350	521	471	129	120	650	591	9.08	9.60	6.98 (2)
6" MagSorbent	30	300	148	0.3	195	1194	970	327	239	1521	1209	20.51	18.76	26.91
6" MagSorbent	50	312	185	0.8	460	1206	1070	292	267	1498	1337	10.75	11.28	8.56
6" MagSorbent	80	356	246	2.6	870	1206	1110	293	290	1499	1400	6.60	7.96	1.02
6" MagSorbent	100	388	240	3.4	1600	1180	1144	302	302	1482	1446	2.43	3.05	0.00
6" MagSorbent + NH3	50	360	266	0.7	800	1190	960	279	193	1469	1153	21.51	19.33	30.82 (3)
6" MagSorbent + NH3	100	395	290	3.4	1700	1180	1111	253	230	1433	1341	6.42	5.85	9.09 (3)
9" Vermiculite	50	345	263	NT	750	1123	1103	284	284	1407	1387	1.42	1.78	0.00
9" Vermiculite	80	360	270	NT	1125	1133	1110	284	284	1417	1394	1.62	2.03	0.00
9" Vermiculite	100	375	282	NT	1800	1153	1123	276	276	1429	1399	2.10	2.60	0.00
9" Vermiculite + NH3	50	342	265	NT	575	1180	1080	307	239	1487	1319	11.30	8.47	22.15 (4)
9" Vermiculite + NH3	100	380	316	NT	1200	1200	1136	262	241	1462	1377	5.81	5.33	8.02
6" Activated Carbon	30	303	132	0.4	350	1160	310	210	74	1370	384	71.97	73.28	64.76
6" Activated Carbon	50	318	136	1.1	490	1211	670	319	122	1530	792	48.24	44.67	61.76
6" Activated Carbon	80	363	155	2.9	975	1228	890	324	155	1552	1045	32.67	27.52	52.16
6" Activated Carbon	100	379	179	3.9	1280	1230	1030	328	245	1558	1275	18.16	16.26	25.30
6" Activated Carbon + NH3	50	342	143	1.0	580	1440	1430	375	375	1815	1805	0.55	0.69	0.00
6" Activated Carbon + NH3	100	383	198	4.0	1600	1195	1045	300	271	1495	1316	11.97	12.55	9.67
3" MagSorbent + 6" Act Carbon	30	199	117	0.5	50	518	123	193	12	711	135	81.01	76.25	93.78
3" MagSorbent + 6" Act Carbon	50	220	120	1.2	260	520	190	193	20	713	210	70.55	63.46	89.64
3" MagSorbent + 6" Act Carbon	80	252	125	3.4	540	516	391	116	31	632	422	33.23	24.22	73.28
3" MagSorbent + 6" Act Carbon	100	273	122	4.6	850	522	480	128	71	650	551	15.23	8.05	44.53

(1) NH_3: 550 ppm In & 150 ppm Out (2) NH_3: 450 ppm In & 250 ppm Out (3) NH_3: Slip Noted (4) NH_3: 1[illegible]00 ppm In & High Out NT - Not Taken

TABLE C-1 (CONTINUED)
STATIONARY DIESEL ENGINE FIELD TEST RESULTS

Bed Composition	Fan Setting	Temperature (Deg F) In	Temperature (Deg F) Out	dP Across Bed (in H2O)	Duct Velocity (fpm)	CO (ppm) In	CO (ppm) Out	% CO Removal	O2 (%) In	O2 (%) Out	Bed Velocity (fps)	Adj'd* % NOx Removal	
3" Vermiculite + 6" Act Carbon	30	186	91	0.5	70	162	143	11.73	16.7	16.7	0.13	86.87	
3" Vermiculite + 6" Act Carbon	50	211	102	1.1	225	167	155	7.19	16.7	16.7	0.41	71.30	
3" Vermiculite + 6" Act Carbon	80	252	125	3.4	650	167	155	7.19	16.7	16.7	1.18	69.39	
3" Vermiculite + 6" Act Carbon	100	266	144	5.4	950	167	150	10.18	16.7	16.7	1.73	35.54	
3" Vermiculite + 6" MagSorbent	30	284	255	0.3	250	78	37	52.56	15.6	16.0	0.46	59.01	
3" Vermiculite + 6" MagSorbent	50	298	245	0.8	450	74	64	13.51	14.7	14.9	0.82	22.56	
3" Vermiculite + 6" MagSorbent	80	348	204	3.0	750	79	75	5.06	13.6	13.6	1.37	5.50	
3" Vermiculite + 6" MagSorbent	100	374	252	3.7	1350	80	80	0.00	13.6	13.6	2.46	3.02	
9" MagSorbent	50	235	170	1.0	490	169	155	8.28	16.7	16.6	0.89	8.72	
9" MagSorbent + NH3	50	245	194	1.0	490	162	157	3.09	16.6	16.6	0.89	10.25	(1)
9" MagSorbent + NH3	100	262	200	3.9	1350	160	160	0.00	16.9	16.9	2.46	9.08	(2)
6" MagSorbent	30	300	148	0.3	195	77	73	5.19	13.6	13.7	0.35	19.39	
6" MagSorbent	50	312	185	0.8	460	81	77	4.94	13.6	13.8	0.84	8.20	
6" MagSorbent	80	356	246	2.6	870	81	81	0.00	13.6	13.6	1.58	6.60	
6" MagSorbent	100	388	240	3.4	1600	83	83	0.00	13.7	13.7	2.91	2.43	
6" MagSorbent + NH3	50	360	266	0.7	800	85	72	15.29	13.6	15.0	1.46	2.57	(3)
6" MagSorbent + NH3	100	395	290	3.4	1700	89	75	15.73	13.7	13.8	3.09	5.08	(3)
9" Vermiculite	50	345	263	NT	750	88	88	0.00	13.5	13.5	1.37	1.42	
9" Vermiculite	80	360	270	NT	1125	88	85	3.41	13.5	13.5	2.05	1.62	
9" Vermiculite	100	375	282	NT	1800	83	85	-2.41	13.6	13.5	3.28	3.44	
9" Vermiculite + NH3	50	342	265	NT	575	78	77	1.28	13.5	13.6	1.05	10.07	(4)
9" Vermiculite + NH3	100	380	316	NT	1200	87	86	1.15	13.6	13.6	2.18	5.81	
6" Activated Carbon	30	303	132	0.4	350	73	56	23.29	13.8	14.0	0.64	71.97	
6" Activated Carbon	50	318	136	1.1	490	80	80	0.00	13.6	13.6	0.89	48.24	
6" Activated Carbon	80	363	155	2.9	975	82	82	0.00	13.8	14.0	1.77	30.69	
6" Activated Carbon	100	379	179	3.9	1280	108	80	25.93	13.8	15.2	2.33	-2.29	
6" Activated Carbon + NH3	50	342	143	1.0	580	95	100	-5.26	13.7	14.3	1.06	-8.63	
6" Activated Carbon + NH3	100	383	198	4.0	1600	78	101	-29.49	13.6	14.7	2.91	-3.90	
3" MagSorbent + 6" Act Carbon	30	199	117	0.5	50	151	166	-9.93	16.7	16.7	0.09	81.01	
3" MagSorbent + 6" Act Carbon	50	220	120	1.2	260	159	160	-0.63	16.8	16.7	0.47	71.27	
3" MagSorbent + 6" Act Carbon	80	252	125	3.4	540	166	155	6.63	16.8	16.7	0.98	34.86	
3" MagSorbent + 6" Act Carbon	100	273	122	4.6	850	160	160	0.00	16.8	16.8	1.55	15.23	

(1) NH_3: 550 ppm In & 150 ppm Out (2) NH_3: 450 ppm In & 250 ppm Out (3) NH_3: Slip Noted (4) NH_3: 1100 ppm In & High Out NT - Not Taken

* NOx removals based on the assumptions that some air leakage or dilution occurred in the system and that the O_2 level of exhaust gas did not change upon passing through the filters.

TABLE C-2
FIELD TEST RESULTS WITH
A MOBILE DIESEL GENERATOR

Bed Composition	Fan Setting	Temperature (Deg F) In	Temperature (Deg F) Out	dP Across Bed (in H2O)	Duct Velocity (fpm)	NOx (ppm) In	NOx (ppm) Out	% NOx Removal	O2 (%) In	O2 (%) Out	Bed Velocity (fps)	Adj'd* % NOx Removal
3" Verm + 6" Act Carb	30	216	62	1.0	210	69	13	81.16	18.9	18.7	0.38	82.95
3" Verm + 6" Act Carb	50	320	127	1.5	450	46	34	26.09	19.1	19.0	0.82	30.19
3" Verm + 6" Act Carb	100	336	144	6.5	1250	80	79	1.25	19.2	19.3	2.28	-5.33
3" Verm + 6" Act Carb	80	335	234	5.8	1150	83	79	4.82	19.3	19.4	2.09	-1.98
3" Verm + 6" Act Carb	50	326	250	4.2	700	87	86	1.15	19.4	19.3	1.27	7.74
3" Verm + 6" Act Carb	30	284	86	2.2	400	46	22	52.17	19.4	19.4	0.73	52.17
3" Verm + 6" Act Carb	50	318	130	2.8	900	62	62	0.00	19.2	19.2	1.64	0.00
3" Verm + 6" Act Carb	80	328	135	4.4	975	88	88	0.00	19.2	19.2	1.77	0.00
3" Verm + 6" Act Carb	80	346	137	4.5	1000	41	63	-53.66	20.0	19.3	1.82	18.05
3" Verm + 6" Act Carb	50	329	140	3.2	750	69	90	-30.43	19.2	19.2	1.37	-30.43

* NOx removals based on the assumptions that some air leakage or dilution occurred in the system and that the O2 level of exhaust gas does not change upon passing through the filters.

TABLE C-3
SIMULATED BURNER-HEATER TEST RESULTS

Bed Composition	Fan Setting	Temperature (Deg F) In	Temperature (Deg F) Out	Duct Velocity (fpm)	NOx (ppm) In	NOx (ppm) Out	% NOx Removal	CO (ppm) In	CO (ppm) Out	% CO Removal	O2 (%) In	O2 (%) Out	Bed Velocity (fps)	Adj'd* % NOx Removal
3" MagSorbent	85	265	200	2000	31	28	9.68	58	45	22.41	18.5	18.5	3.64	9.68
3" MagSorbent	50	292	211	750	54	27	50.00	900	400	55.56	16.8	18.8	1.37	0.00
3" MagSorbent	50	298	206	750	54	27	50.00	441	250	43.31	16.8	18.8	1.37	0.00
3" MagSorbent	70	331	237	1450	43	31	27.91	100	86	14.00	18.1	18.6	2.64	11.52
3" MagSorbent	70	356	261	1500	42	31	26.19	81	81	0.00	18.0	18.6	2.73	6.06
3" MagSorbent	70	378	275	1600	46	31	32.61	153	120	21.57	17.7	18.6	2.91	5.04
3" MagSorbent	70	390	282	1620	46	31	32.61	183	138	24.59	17.7	18.7	2.95	0.52
3" MagSorbent	85	405	296	2500	39	35	10.26	63	58	7.94	18.4	18.5	4.55	6.35
3" Activated Carbon	100	347	142	1600	43	43	0.00	149	120	19.46	17.9	17.8	2.91	3.33
3" Activated Carbon	85	374	173	1400	50	50	0.00	287	243	15.33	17.4	17.4	2.55	0.00
3" Activated Carbon	90	381	277	1600	31	42	-35.48	107	76	28.97	19.1	18.1	2.91	14.70
3" Activated Carbon	90	378	277	1600	42	46	-9.52	55	55	0.00	18.3	18.1	2.91	0.00
3" Activated Carbon	80	377	273	1300	50	50	0.00	29	86	-196.55	18.5	18.5	2.37	0.00
3" Activated Carbon	80	377	269	1300	50	50	0.00	26	34	-30.77	18.4	18.4	2.37	0.00
3" Activated Carbon	70	373	255	900	57	57	0.00	68	84	-23.53	17.9	17.9	1.64	0.00
3" Activated Carbon	70	224	190	800	28	28	0.00	0	0	0.00	20.8	20.8	1.46	0.00
3" Activated Carbon	50	200	160	400	55	43	21.82	0	0	0.00	20.8	20.8	0.73	21.82
3" Activated Carbon	50	196	156	400	55	39	29.09	0	0	0.00	20.8	20.8	0.73	29.09
3" Activated Carbon	70	187	155	800	32	28	12.50	0	0	0.00	20.8	20.8	1.46	12.50
3" Activated Carbon	50	180	143	400	53	39	26.42	0	0	0.00	20.8	20.8	0.73	26.42

* NOx removals based on the assumptions that some air leakage or dilution occurred in the system and that the O2 level of exhaust gas does not change upon passing through the filters.